Properties of Near-Infrared Selected AGN Candidates with 2MASS/ROSAT Catalogues

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ABSTRACT
We report on the near-infrared selected AGN candidates extracted from 2MASS/ROSAT catalogues and discuss their properties. First, near-infrared counterparts of a X-ray source in ROSAT catalogues (namely, Bright Source Catalogue (BSC) and Faint Source Catalogue (FSC)) were extracted by positional cross-identification of $\leq 30''$. Because these counterparts would contain many mis-identifications, we further imposed near-infrared colour selection criteria and extracted reliable AGN candidates (BSC: 5,273, FSC: 10,071). Of 5,273 (10,071) candidates in the BSC (FSC), 2,053 (1,008) are known AGNs. Near-infrared and X-ray properties of candidates show similar properties with known AGNs and are consistent with previous studies. We also searched for counterparts in other wavelengths (that is, optical, near-infrared, and radio), and investigated properties in multiwavelength. No significant difference between known AGNs and unclassified sources could be seen. However, some unclassified sources in the FSC showed slightly different properties compared with known AGNs. Consequently, it is highly probable that we could extract reliable AGN candidates though candidates in the FSC might be spurious.

Key words: galaxies: active – galaxies: quasars: general – catalogues

1 INTRODUCTION
Active galactic nuclei (AGNs) are luminous in wide wavelength because of the vast amount of energy produced by accretion onto a central supermassive blackhole. Accordingly, they are observable at nearly entire wavelength despite locating at great distances, and have been searched in various wavelengths: e.g., optical (Schneider et al. 2007; Véron-Cetty & Véron 2006), infrared (Low et al. 1988, 1989), or radio (Frayer et al. 2004). X-ray emission is especially a characteristic property of AGNs. The vast majority of X-ray sources are AGNs and all classes of AGNs appear in X-ray surveys. There are many studies that collect AGN samples using X-ray data (e.g., Kim & Elvis 1998; Watanabe et al. 2004; Polletta et al. 2007). Therefore, whether an object is a X-ray source can be a criterion to select AGNs.

Colour selection is a powerful technique in extracting AGN candidates. A classical method is known as the UV-excess (UVX; Sandage 1965; Schmidt & Green 1983; Boyle et al. 1990), which extract bluer quasars. Richards et al. (2002) selected quasars via their nonstellar colours using SDSS photometry. Other selections are such as red quasar survey using optical and near-infrared combined colours (Glikman et al. 2007), or mid-infrared selected AGNs using Spitzer data (Lacy et al. 2004; Stern et al. 2005).

Colour selection using near-infrared photometry has also performed by some previous studies. Cutri et al. (2001, 2002) extracted obscured AGN candidates using the colour selection of $(J - K_s) > 2.0$. The $KX$ method using the excess in K-band, proposed by Warren et al. (2000), was used for extracting quasars (Jurek et al. 2008; Maddox et al. 2008; Smail et al. 2008; Nakos et al. 2009). However, these extracted only peculiar AGNs (in the former case) or extracted AGNs using combined with optical photometry (in the latter case). Because the optical light suffers more extinctions than the infrared light and an AGN is surrounded by a dust torus, a selection using optical and near-infrared combined colours may miss AGNs (especially obscured AGNs), because of lack of optical detection. However, Kouzuma & Yamaoka (2010) proposed colour selection criteria to extract AGNs using only near-infrared colours. They demonstrated by both observed and simulated colours that AGNs are differentiated from several types of objects in a $(H - K_s) - (J - H)$ colour-colour diagram (CCD). This enables us to extract AGN candidates using only near-infrared photometry.

In this paper, we first extract bright sources in both near-infrared and X-ray by a cross-identification between the Two Micron All Sky Survey (2MASS) and ROSAT all-sky survey catalogues, and select AGN candidates on the basis of the near-infrared colour selection criteria proposed by Kouzuma & Yamaoka (2010). In addition, we investigate properties of candidates using not only near-infrared and X-ray data but also photometric data at other wavelengths derived by cross-identifications with some catalogues. In Section 2 we introduce the 2MASS and ROSAT. In Section 3 we describe the method to extract AGN candidates (including the
criteria of both cross-identification and colour selection) and the results. In Section 4 properties of AGN candidates are investigated by photometric data at near-infrared, X-ray, and other wavelengths.

2 DATA

2.1 2MASS

The 2MASS (Skrutskie et al. 2006) is a project that observed 99.998% of the whole sky at J (1.25 μm), H (1.65 μm), Ks (2.16 μm) bands, at Mt. Hopkins, AZ (in the Northern Hemisphere) and at CTIO, Chile (in the Southern Hemisphere) between 1997 June and 2001 February. The instruments are both highly automated 1.3-m telescopes equipped with three-channel cameras, each channel consisting of a 256 × 256 array of HgCdTe detectors. The 2MASS obtained 4,121,439 FITS images (pixel size ∼ 2′′0) with 7.8 s of integration time. The limiting magnitudes (Signal-to-Noise Ratio (S/N) > 10) are 15.8 (J), 15.1 (H), 14.3 (Ks) mag at each band. The Point Source Catalogue (PSC) was produced using these images and catalogued 470,992,970 sources. In the 2MASS web site, the images and the PSC are open to the public and are easily available.

2.2 ROSAT

The ROSAT is an X-ray astronomical satellite launched in 1990. During six months soon after the launching, all-sky imaging survey in the energy range of 0.1 − 2.4 keV was performed with a X-ray reflector equipped with Position Sensitive Proportional Counter (PSPC). A limiting PSPC count-rate is 0.05 cts s⁻¹. This is the first imaging survey in the X-ray wavelength. The survey has yielded Bright Source Catalogue (BSC) and Faint Source Catalogue (FSC), and they contain 18,806 and 105,926 sources, respectively, with positional error of ≲ 30″. Both catalogues have already been open to the public and available on the web. In this paper, we use both BSC and FSC.

3 EXTRACTION OF AGN CANDIDATES

3.1 Cross-identification

We cross-identified ROSAT catalogues with the 2MASS PSC to extract a near-infrared counterpart for a X-ray source. We set a positional criterion of ≲ 30″, that is, we treat as a near-infrared counterpart when a 2MASS source is within 30″ of a ROSAT source. As a result of the cross-identification, we extracted 46,205 (217,033) sources. Even though several 2MASS sources may be located within 30″ of a ROSAT source, we treated them as counterparts for the X-ray source. Accordingly, in the positional criterion of ≲ 30″, many objects are miss-identified due to the difference of angular resolutions. Therefore, we further imposed colour selection criteria to extract reliable counterparts.

3.2 Colour Selection

The difference between positional accuracies causes mis-identification on a cross-identification. Therefore, another criterion is required for accurately extracting a counterpart. Bessell & Brett (1988) presented stellar locus in a near-infrared (H−Ks)-(J−H) CCD. Because most 2MASS sources are galactic normal stars, mis-identified sources should be located around the stellar locus in the near-infrared CCD. Kouzuma & Yamaoka (2010) investigated near-infrared colours of quasars/AGNs and demonstrated that the locus of quasars/AGNs are differentiated from the stellar locus in the near-infrared CCD. They also proposed near-infrared colour selection criteria for extracting AGNs:

\[
\begin{align*}
(J − H) & \leq 1.70(H − Ks) − 0.118 \\
(J − H) & \leq 0.61(H − Ks) + 0.50
\end{align*}
\]

(1)

(2)

We adopted these criteria for extracting reliable AGN candidates from the cross-identified sources. Before the near-infrared colour selection, we extracted the sources having photometric quality flags in the 2MASS PSC superior to B (corresponding to S/N > 7). Samples were reduced to 27,058 (121,767) sources. We subsequently extracted AGN candidates on the basis of the near-infrared colour selection criteria.

Because most sources with $K_s < 10$ are probably normal stars, we further ruled out such sources (i.e., extracted only sources with $K_s \geq 10$).

3.3 Extracted Candidates

Finally, we have extracted 5,273 (10,071) sources as AGN candidates in the BSC (FSC). To confirm that candidates have been already known, we checked the following AGN catalogues: Véron-Cetty & Véron (2006); Schneider et al. (2007); Anderson et al. (2007); Brinkmann et al. (2000); Wei et al. (1999); Yuan et al. (1998).

Table 1 shows the number of identified sources in each catalogue. Of 5,273 (10,071) candidates, 2,053 (1,008) sources have analogues: Véron-Cetty & Véron (2006); Schneider et al. (2007); Anderson et al. (2007); Brinkmann et al. (2000); Wei et al. (1999); Yuan et al. (1998).

4 PROPERTIES OF AGN CANDIDATES

4.1 Near-Infrared and X-ray Properties

We investigate near-infrared and X-ray properties of the AGN candidates. The zero-magnitudes of near-infrared fluxes at three bands are already known as AGNs. It is highly probable that remaining candidates in the BSC (FSC). To confirm that candidates have been already known, we checked the following AGN catalogues: Véron-Cetty & Véron (2006); Schneider et al. (2007); Anderson et al. (2007); Brinkmann et al. (2000); Wei et al. (1999); Yuan et al. (1998).

Table 1 shows the number of identified sources in each catalogue. Of 5,273 (10,071) candidates, 2,053 (1,008) sources have been already known as AGNs. It is highly probable that remaining 3,220 (9,693) sources are unknown AGNs. Below, we consider the reliability of AGN candidates by investigating properties of them.
red AGNs in the BSC (FSC) and it is highly probable that they are AGNs at (Cutri et al. 2001). It is believed that many red AGNs are found K

$4.1.2$ Hardness Ratio

Figure 1. X-ray flux versus K-band magnitude. The left panel is the distributions of candidates in the BSC and the right panel is those in the FSC. The symbols represent known AGNs in the BSC (blue crosses), known AGNs in the FSC (red crosses), and unclassified sources in both BSC and FSC (gray circles).

A similarity between candidates in the BSC and the FSC is that $F_X/F_S$ decreases with $(J-K_S)$ colour. This is probably due to extinctions because the light at the J-band suffers extinction than the light at the K$_S$ band (i.e., $F_X$ should be absorbed than $F_S$).

Bernt Haakonsen & Rutledge (2009) reported loci of various types of objects in a $(J-K_S)-(F_X/F_S)$ diagram using both 2MASS photometry and X-ray flux in the ROSAT BSC. Their diagram shows that the AGN locus is well separated from those of other types of objects such as normal stars, where almost all of the AGNs have $(J-K_S) > 0.6$ and $F_X/F_S > 3 \times 10^{-2}$. The locus of our candidates is consistent with their AGN locus.

Some unclassified sources in the BSC or the FSC have $(J-K_S) < 1.0$, where few known AGNs are distributed. These sources might be spurious AGNs or other kinds of AGNs (e.g., AGNs having extremely small extinction and low luminosity) that have not been found by previous surveys.

The AGNs with $(J-K_S) > 2.0$ are defined as red AGNs (Cutri et al. 2001). It is believed that many red AGNs are found at $z \lesssim 0.5$ (Cutri et al. 2002). In our sample, there are 234 (192) red AGNs in the BSC (FSC) and it is highly probable that they are AGNs at $z \lesssim 0.5$.

$4.1.2$ Hardness Ratio

Figure 3 shows histograms of two hardness ratios (HR1 and HR2), where HR1 and HR2 are given using four energy bands, that is, A (Pulse Height Amplitude (PHA) channels 11–41), B (52–201), C (52–90), and D (91–201): $HR1=(B-A)/(B+A)$ and $HR2=(D-C)/(D+C)$, respectively. In the HR1 histogram for the BSC, both known AGNs and unclassified sources show a flat distribution in $-0.5 \leq HR1 \leq 1.0$ and the number of sources decreases in $HR1 \lesssim -0.5$, although the number of unclassified sources is relatively larger in $HR1 \gtrsim 0.8$. Voges et al. (1999) presented that X-ray counterparts for AGNs in the catalogue of Veron-Cetty & Veron (1998) show a flat distribution in the range between $-0.5$ to $+1.0$. Hence, the HR1 property of these candidates is consistent with Voges et al. (1999). On the other hand, although known AGNs in the FSC have a similar shape in Voges et al. (1999), the number of unclassified sources in the FSC increase towards larger HR1 values (i.e., they are relatively harder as compared to known AGNs). Therefore, some candidates in the FSC might be contaminated by galaxies because Abell clusters of galaxies (ACO) objects tend to have harder than stars and AGNs in their diagrams (Voges et al. 1999). In the HR2 histograms, they have peaks at $HR2 \sim 0.2$ and this is also consistent with the HR2 histograms of AGNs in Voges et al. (1999). It should be noted that in the range over $HR2 \sim 0.2$ there are relatively large number of unclassified candidates in the BSC than known AGNs (i.e., there are harder samples) though the distributions for known/unknown sources in the FSC are alike.

In Figure 4 HR1 versus HR2 diagrams are shown. Both known AGNs and unclassified sources in the BSC have similar distribution each other, although there are a relatively large number of unclassified sources in HR1 $\gtrsim 0.8$ as pointed out the above. Most

| AGN catalogue | BSC | FSC |
|---------------|-----|-----|
| Quasars and Active Galactic Nuclei (12th Ed.) (Véron-Cetty & Véron 2006) | 1,900 | 871 |
| SDSS-DR5 quasar catalog (Schneider et al. 2007) | 493 | 343 |
| AGN from RASS and SDSS DR5 (Anderson et al. 2007) | 776 | 537 |
| ROSAT-FIRST AGN correlation (Brinkmann et al. 2000) | 171 | 108 |
| RASS AGN sample (Wei et al. 1999) | 110 | 0 |
| ROSAT detected quasars II (Yuan et al. 1998) | 104 | 32 |
| total known sources | 2,053 | 1,008 |

Table 1. The number of known AGNs in our AGN candidates.
AGNs are observable in multiwavelength. Accordingly, counterparts at other wavelengths provide us with information about their properties. To find multiwavelength counterparts of AGN candidates, the candidates were positionally cross-identified with the following catalogues: Sloan Digital Sky Survey (SDSS) Photometric Catalog, Release 7 (Adelman-McCarthy et al. 2008, Adelman-McCarthy & et al. 2009), 3rd release of the Deep Near Infrared Survey of the southern sky (DENIS) database (DENIS consortium, 2005), Faint Images of the Radio Sky at Twenty-centimeters (FIRST) Survey Catalog, Version 0.3April (White et al. 1997), and 1.4GHz National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998). Table 2 summarizes the number of counterparts in each catalogue.

### 4.2 Properties of Counterparts

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#### 4.2.1 Optical Properties

Of 1,857 (2,028) SDSS counterparts in the BSC (FSC), 624 (1,301) are unclassified sources. Here, we investigate photometric properties using SDSS photometry. Figure 5 shows histograms of $u'$ magnitudes in the SDSS catalogue. Unclassified sources are relatively fainter than known AGNs. This is because the search in the near-infrared/X-ray, in which light suffers smaller extinction than in the optical, enables us to detect faint sources in the optical wavelength.

In Figure 6 we plotted candidates on a $(u' - g')-(g' - r')$ CCD. There are several studies investigating stellar locus in a CCD using SDSS photometry (e.g., Fan 1999, Finlator et al. 2000, Sesar et al. 2008). Their stellar loci are consistent with each other. Anderson et al. (2003, 2007) also investigated distributions of normal stars, AGNs, and quasars in the $(u' - g')-(g' - r')$ CCD, and demonstrated that loci of quasars/AGNs are separated from the stellar locus. The locus of sample stars, taken from the SDSS catalogue, is also shown in Figure 6. The reddening vector is based on Fukugita et al. (2004). Almost all of the known AGNs in both catalogues are clearly separated from the stellar locus. Although

#### Table 2. The number of counterparts extracted from each catalogue. The numbers in parentheses are unclassified sources.

| catalogue | positional criterion | number |
|-----------|---------------------|--------|
| SDSS      | $\leq 1''$          | 1,857 (624) 2,028 (1,301) |
| DENIS     | $\leq 1''$          | 1,949 (1,443) 3,902 (3,722) |
| FIRST     | $\leq 2''$          | 592 (106) 381 (159) |
| NVSS      | $\leq 2''$          | 534 (190) 383 (244) |

![Figure 3. Histograms of hardness ration HR1 (top panel) and HR2 (bottom panel). The number of sources are normalized. The left panels are histograms of known AGNs (blue dotted line) and unclassified sources (gray solid line) in the BSC. The right panels are histograms of known AGNs (red dotted line) and unclassified sources (gray solid line) in the FSC.](image1)

![Figure 4. HR1 versus HR2 diagrams. The symbols are same as in Figure 1](image2)

![Figure 5. Histograms of $u'$ magnitudes. The number of sources are normalized. The symbols are the same as in Figure 3](image3)

![Figure 6. Properties of Counterparts](image4)
most unclassified sources are not located at the stellar locus, some sources are distributed around the stellar locus. It is noticeable for unclassified sources in the FSC. These sources might not be AGNs but normal stars.

We can notice that some unclassified sources are located in \((u' - g') > 1.5\) (especially, around \((u' - g') \sim 2.0\)), where few known AGNs are distributed. Most of these sources are still differentiated from the stellar locus. These might be highly reddened AGNs or other types of AGNs that are not discovered in SDSS surveys. We note that most of the unclassified sources with \((u' - g') < 1.5\) are probably newly discovered AGNs.

### 4.2.2 Near-Infrared Variability

AGNs are known to have variability across wide wavelength ranges from radio to X-ray or \(\gamma\)-ray \cite{Krolik1991, Edelson1996, Giveon1999}. Here, we investigate variability of AGN candidates in the near-infrared wavelength, by comparing magnitudes between 2MASS and DENIS.

Figure 7 shows \(J - \Delta J\) and \(K_S - \Delta K_S\) diagrams, where \(\Delta J = J_{\text{2MASS}} - J_{\text{DENIS}}\) and \(\Delta K_S = K_{S,\text{2MASS}} - K_{S,\text{DENIS}}\), respectively. We also plotted photometric differences of normal stars for referring to typical difference between 2MASS and DENIS photometric systems. Sample stars are taken from \(l = 260^\circ, b = +3^\circ\) area, whose near-infrared colours are consistent with those of normal stars in \cite{Bessell1988}. We note that the sample stars have photometric quality flags in both 2MASS and DENIS catalogues superior to B \((S/N > 7)\) and 90, respectively. The DENIS photometry is transformed into the 2MASS photometry on the basis of \cite{Carpenter2001}. Standard deviations \(\sigma_{\Delta J}\) and \(\sigma_{\Delta K_S}\) for the sample stars are 0.08 and 0.20, respectively. As seen in the diagrams, there are several sources clearly showing variability. Table 3 summarizes the number of candidates showing variability larger than \(3\sigma\) and \(5\sigma\). In our sample, percentages of candidates with variability in the FSC are relatively smaller than those in the BSC. Faint AGNs at the X-ray possibly show less variability. We note that, practically, there should be more sources with variability because we could compare only double-epoch magnitudes.

### 4.2.3 Radio Properties

Figure 8 shows flux ratios \(F_{\text{radio}} / F_{\text{radio}}\) versus \(F_{\text{radio}} / F_{\text{radio}}\) diagram. Significant differences between known AGNs and unclassified sources can not be clearly seen in each diagram. There appears to be correlations between \(l_{\text{radio}}\) and \(l_{\text{radio}}\) in the diagrams. We performed least
square fittings for the distributions of both known AGNs and unclassified sources. The least square fitting lines are also shown in the diagrams. Still, there is no significant difference between known AGNs and unclassified sources in each diagram, although in the diagrams there is small difference in slope. It is known that there is a correlation between luminosity ratios $L_\text{X}/L_\text{R}$ and $L_\text{k}/L_\text{R}$ (e.g., Brinkmann et al. [1993, 1997, 2000]). Correlations in our sample may be a variant of such correlations.

Because unclassified sources have similar properties with known AGNs in the diagrams, these properties also support that unclassified sources are AGNs.

5 SUMMARY AND CONCLUSIONS

We have cross-identified the 2MASS PSC with ROSAT catalogues, and have extracted AGN candidates on the basis of the near-infrared colour selection. Of 5,273 (10,701) AGN candidates in the BSC (FSC), 3,220 (9,693) are unclassified sources. We investigated their properties using near-infrared, X-ray, optical, and radio data. Overall, most unclassified sources in the BSC have similar properties with known AGNs and their properties are also consistent with previous studies, whereas some unclassified sources, especially those in the FSC, have properties different from known AGNs.

It is highly probable that most unclassified sources are AGNs because of the following reasons. First, our candidates are X-ray sources. The fact that a object is an X-ray source supports the object is an AGN because it is believed that the vast majority of X-ray sources are AGNs. Second, our candidates satisfy the near-infrared colour selection criteria proposed by Kouzuma & Yamaoka [2010], that is, they have properties in near-infrared colours similar to those of AGNs. Third, some candidates have been already known AGNs and not only unclassified sources show properties similar to those of known AGNs but also their properties in multiwavelength are consistent with previous studies. However, it should be noted that there may be relatively large number of contamination in unclassified FSC sources. To confirm that they are real AGNs, spectroscopic observations are required.

Similar works using a cross-identification with a ROSAT catalogue were performed by Boller et al. [1992b, 1998]. Boller et al. [1992b] extracted a sample of 14,708 extragalactic IRAS sources on the basis of a supervised selection whose selection quality was assessed by Boller et al. [1992d], and they cross-identified between the sample and the first processing of the ROSAT all-sky survey data. The cross-identified 244 IRAS galaxies comprised infrared luminous nearby galaxies, spirals and ellipticals, Seyfert galaxies, and QSOs. They investigated properties of the cross-identified sources using X-ray, far-infrared, and optical fluxes, and found some correlations between them. The work in Boller et al. [1998] is also similar to that in Boller et al. [1992b], which cross-identified the 14,315 IRAS galaxies with the second processing of the ROSAT all-sky survey. These studies are similar to our study in that a ROSAT catalogue is cross-identified with an infrared catalogue. However, whereas these studies investigated extragalactic sources extracted by a mid- and far-infrared colour selection, we investigated AGN candidates extracted by the near-infrared colour selection. The number of sample is also totally different. In addition, we discussed not only properties in infrared and X-ray but also near-infrared variability and radio properties, which are not discussed in Boller et al. [1992b, 1998].

This paper extracted several thousands of AGN candidates across the entire sky. The use of only near-infrared colours enables us to search for AGN candidates across the entire sky. When using this technique on other deep near-infrared surveys such as DENIS, UKIDSS, and future surveys, many AGNs, which have not been detected in the optical wavelength, can be extracted.

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