ON \( R – W \) AS A DIAGNOSTIC TO DISCOVER OBSCURED ACTIVE GALACTIC NUCLEI IN WIDE-AREA X-RAY SURVEYS

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ABSTRACT

Capitalizing on the all-sky coverage of WISE and the 35% and 50% sky coverage from Sloan Digital Sky Survey and Pan-STARRS, respectively, we explore the efficacy of \( m_{R}(\text{optical}) – m_{3.4\,\mu\text{m}} \) (mid-infrared), hereafter \( R – W \), as a color diagnostic to identify obscured supermassive black hole accretion in wide-area X-ray surveys. We use the ≈16.5 deg\(^2\) Stripe 82 X-ray survey data as a test bed to compare \( R – W \) with \( R – K \), an oft-used obscured active galactic nucleus (AGN) selection criterion, and examine where different classes of objects lie in this parameter space. Most stars follow a well-defined path in \( R – K \) versus \( R – W \) space. We demonstrate that optically normal galaxies hosting X-ray AGNs at redshifts 0.5 < \( z < 1 \) can be recovered with an \( R – W > 4 \) color cut, while they typically are not selected as AGNs based on their \( R – W \) colors. Additionally, different observed X-ray luminosity bins favor different regions in \( R – W \) parameter space: moderate-luminosity AGNs \((10^{43} \text{ erg s}^{-1} < L_{0.5–10 \text{ keV}} < 10^{44} \text{ erg s}^{-1})\) tend to have red colors, while the highest-luminosity AGNs \((L_{0.5–10 \text{ keV}} > 10^{44} \text{ erg s}^{-1})\) have bluer colors; higher spectroscopic completeness of the Stripe 82X sample is needed to determine whether this is a selection effect or an intrinsic property. Finally, we parameterize X-ray obscuration of Stripe 82X AGNs by calculating their hardness ratios (HRs) and find no clear trends between HR and optical reddening. Our results will help inform best-effort practices in following up obscured AGN candidates in current and future wide-area, shallow X-ray surveys, including the all-sky eROSITA mission.

Key words: galaxies: active – infrared: galaxies – quasars: general – quasars: supermassive black holes – X-rays: galaxies – X-rays: general

1. INTRODUCTION

Supermassive black holes growing via accretion (active galactic nuclei, or AGNs) are often identified by telltale signatures in their spectra, such as Doppler-broadened emission lines from gas orbiting near the black hole or strong narrow emission lines in gas hundreds of parsecs away from the black hole, yet still primarily ionized by the AGN continuum. The former “broad-lined” AGNs are easily discovered by large ground-based optical surveys, such as the Sloan Digital Sky Survey (SDSS), which targeted objects based on optical photometry for follow-up spectroscopy, revealing hundreds of thousands of AGNs with “blue” colors and point-like morphology (York et al. 2000; Schneider et al. 2002; Pâris et al. 2014). Conversely, obscured AGNs represent those sources where the active nucleus is enshrouded, and they can come in two flavors: objects lacking broad emission lines but displaying powerful narrow emission lines indicative of supermassive black hole accretion, i.e., the Type 2 AGNs explained by the AGN unification model (Antonucci 1993; Urry & Padovani 1995), and those sources with broad emission lines but “red” colors owing to large amounts of dust attenuating and reddening the optical continuum light (e.g., Glikman et al. 2004); here the spectral energy distribution (SED) at optical wavelengths is suppressed with respect to the near- to mid-infrared emission. Many accreting supermassive black holes generate powerful X-ray emission visible across the universe, making X-ray selection an efficient mechanism for obtaining clean AGN samples with virtually no contamination from star-forming
galaxies at X-ray luminosities exceeding $10^{42}$ erg s$^{-1}$ (see Brandt & Alexander 2015 for a recent review), complementing the AGN census revealed from optical and infrared surveys. However, as hard X-rays can select both the unobscured and obscured AGN populations (though the most heavily obscured, i.e., Compton-thick, AGNs can be missed in X-ray surveys), supporting multiwavelength data are necessary to identify which objects are the obscured systems missing from our current census of supermassive black hole growth. While optical/infrared spectroscopy is the “gold standard” in determining whether or not an X-ray source is an obscured AGN, most X-ray sources lack immediate spectroscopic identifications, and following up all X-ray objects with spectroscopy is expensive and time-consuming. Establishing widely applicable diagnostics to uncover obscured black hole growth is then important for mining these large X-ray and multiwavelength data sets for the most promising candidates to follow up, especially as resources are limited. In addition to current and planned wide-area X-ray surveys, such as the 16.5 deg$^2$ Stripe 82X (LaMassa et al. 2013a, 2013b), the 50 deg$^2$ XM-M-XXL (Pf. Pierre), and the ~877 deg$^2$ XMM-Serendipitous (Rosen et al. 2015) surveys, eROSITA will map the entire sky from 0.5 to 10 keV starting in 2017 (Predehl et al. 2014), revealing millions of AGN candidates (Merloni et al. 2012).

1.1. Identifying Type 2 AGNs

A combination of optical and infrared clues have been used to identify Type 2 AGNs. Below $z = 0.5$, the traditional BPT diagnostic ratios (Baldwin et al. 1981; Veilleux & Osterbrock 1987), ([N II] $\lambda$6584/H$\alpha$ versus [O III] $\lambda$5007/H$\beta$) trace the ionization potential and are thus effective at separating narrow-lined AGNs from star-forming galaxies; tens of thousands of such obscured AGNs have been classified by SDSS with this method (e.g., Kauffmann et al. 2003; Kewley et al. 2006). Recently, He II $\lambda$4686/H$\beta$ versus [N II] $\lambda$6584/H$\alpha$ was introduced as an empirical diagnostic to separate star-forming galaxies from AGNs (Shirazi & Brinchmann 2012).

As H$\alpha$ is redshifted out of the optical bandpass at $z > 0.5$, alternative obscured AGN selection methods using observed optical spectra have been developed to capitalize on the existing rich data sets from wide-area optical surveys, including:

1. rest-frame g - z color versus [Ne iii]/[O iii], which can be applied to $z \sim 1.4$ (TBT; Trouille et al. 2011);
2. stellar mass versus [O iii]/H$\beta$, which can select AGNs up to $z \sim 1$ (Mass-Excitation diagnostic, MEx; Juneau et al. 2011);
3. [O iii] $\lambda$3726+$\lambda$2739/H$\beta$ versus [O iii]/H$\beta$, which is applicable to $z \sim 1$ (Lamareille 2010);
4. strong [Ne v] $\lambda$3426 emission, which can select AGNs to $z \sim 1.5$ (Gilli et al. 2010; Mignoli et al. 2013);
5. a combination of narrow emission lines with FWHM values $<2000$ km s$^{-1}$, ratios of narrow emission lines suggesting AGNs rather than star formation ionization, and a high [O iii] luminosity, which is applicable between $0.3 < z < 0.83$ (Zakamska et al. 2003; Reyes et al. 2008).

Alternatively, candidate narrow-lined AGNs at $z \geq 0.5$ can be identified based on signatures at other wavelengths (e.g., infrared color, infrared/optical colors, X-ray emission) and followed up with ground-based infrared spectroscopy to observe the traditional rest-frame BPT emission lines, where the cosmic BPT diagram can then differentiate between AGNs and star-forming galaxies (Kewley et al. 2013a, 2013b; Kartaltepe et al. 2015).

1.2. Selecting Reddened Broad-lined AGNs

Unlike Type 2 AGNs, so-called “red quasars” have broad emission lines (e.g., Glikman et al. 2004), but their optical spectra are attenuated by dust and thus are not generally targeted by optical spectroscopic surveys following up quasar candidates. These broad lines are generally seen at longer wavelengths (i.e., H$\alpha$ and possibly H$\beta$), which suffer less from dust extinction and host-galaxy dilution, and may be reddened Type 1.8 and 1.9 AGNs, rather than pure Type 1 AGNs, since higher-ionization lines such as Mg ii are narrow or absent (e.g., Brusa et al. 2015). These reddened AGNs are an interesting class of objects, and at least some appear to be in a transition stage between an obscured and unobscured phase within the merger-induced galaxy/black hole co-evolution paradigm (Sanders et al. 1988; Hopkins et al. 2005; Brusa et al. 2010; Banerji et al. 2012; Farrah et al. 2012; Glikman et al. 2012). Indeed, the Hubble Space Telescope followed up a handful of these objects and revealed that they live in train-wreck host galaxies, indicative of merger activity (Urrutia et al. 2008; Glikman et al. 2015). Recent Very Large Telescope (VLT) X-shooter observations of a sample of 10 red quasars unearthed powerful outflows in most of these systems, attributed to AGN winds that may be clearing out obscuring dust (Brusa et al. 2015). Unlike Type 2 AGNs selected via BPT diagnostics, which are generally lower-luminosity objects, such red quasars are the highest-luminosity AGNs at every redshift (Glikman et al. 2012; Banerji et al. 2015).

Combining optical and infrared data is a powerful tool in the search for obscured AGNs, including Type 2 sources and reddened broad-lined objects: dust that attenuates optical signatures of black hole growth re-radiates this emission in the near- to mid-infrared (~1-60 $\mu$m), producing visible effects on the SED. Thus, an object that is optically faint while being infrared bright is a candidate hidden black hole. For instance, an oft-used diagnostic to identify red quasars is a color of $R - K > 4.5$ (Glikman et al. 2004); this has been quite successful in identifying samples of reddened AGNs that are missed by optical-only surveys (e.g., Brusa et al. 2005, 2015; Glikman et al. 2007, 2012, 2013; Georgakakis et al. 2009; Banerji et al. 2012, 2015).

Obscured AGNs, both narrow-lined and reddened broad-lined objects, have also been identified using:

$^{20}$ While [Ne v] is a doublet with emission at 3426 and 3326 Å, [Ne v] $\lambda$3326 has one-third the intensity of [Ne v] $\lambda$3426 (Vanden Berk et al. 2001) and has thus been not used to select samples of obscured AGNs.

$^{21}$ Type 1.8 AGNs have weak broad components to H$\alpha$ and H$\beta$, while Type 1.9 AGNs have a broad component to the H$\alpha$ line only.
1. $R \sim [3.6]$ in tandem with $\log(v_{\mu}F_{\mu}/v_{R}F_{R})$, where $[3.6]$ is the Spitzer magnitude at 3.6 $\mu$m (Fiore et al. 2008, 2009; Yan et al. 2010; Melbourne et al. 2011);
2. $R \sim [4.5]$, where $[4.5]$ is the Spitzer magnitude at 4.5 $\mu$m (Hickox et al. 2007);
3. $R \sim W2$, where $W2$ is the Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010) flux at 4.6 $\mu$m (Stern et al. 2012; Yan et al. 2013; Donoso et al. 2014).

More recently, $R \sim W4$, where $W4$ is the WISE flux at 22 $\mu$m, used in conjunction with nondetections in the WISE W1 (3.4 $\mu$m) and W2 bands (see Eisenhardt et al. 2012; Wu et al. 2012, and Stern et al. 2014 for a discussion of $W1 \sim W2$ dropout sources), have been shown to identify extremely reddened Type 1 quasars (Yan et al. 2013; Ross et al. 2014), though such objects are rare and have a low space density. Additionally, infrared-only colors, such as Spitzer IRAC color selection (Lacy et al. 2004; Stern et al. 2005; Donley et al. 2012) and WISE $W1 \sim W2$ color selection (Stern et al. 2012; Assef et al. 2013), have been adopted to identify both unobscured and obscured AGNs, including Type 2 AGNs locally and at high redshift and high luminosity (e.g., Lacy et al. 2015), though these color selections work best at brighter fluxes since star-forming galaxy contamination becomes significant at fainter fluxes (Barmby et al. 2006; Cardamone et al. 2008; Donley et al. 2008; Mateos 2012; Mendez et al. 2013).

1.3. Widening the Multiwavelength Search to Larger Areas

Though previous optical–mid-infrared colors have been successful in illuminating a unique population of obscured AGNs, they can be limited in scope. For instance, Spitzer observations cover a relatively small area of the sky, limiting the $R \sim [3.6]$ and $R \sim [4.5]$ diagnostics to existing Spitzer survey areas, such as the Spitzer Wide-area InfraRed Extragalactic Survey (SWIRE; Lonsdale et al. 2003), the Great Observatories Origins Deep Survey (GOODS; Treister et al. 2006), COSMOS (Sanders et al. 2007), the Spitzer Deep, Wide-Field Survey (Ashby et al. 2009), the Spitzer South Pole Telescope Deep Field (SSDF; Ashby et al. 2013), the Spitzer Extragalactic Representative Volume Survey (Mauduit et al. 2012), and the Spitzer Public Legacy Survey of the UKIDSS Ultra Deep Survey (SpUDS; Pe. J. Dunlop).

The Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) was an all-sky near-infrared survey, allowing samples of $R \sim K$-selected candidates to be studied (e.g., Glikman et al. 2004), but at a relatively shallow depth compared with UKIDSS. Though the UKIDSS Large Area Survey reaches $\sim$1.5 mag deeper than 2MASS in $K$ band, it is limited in area to $\sim$7500 deg$^2$. The VISTA Hemisphere Survey (McMahon et al. 2013) is surveying the Southern Hemisphere in $J$ and $K$, reaching flux limits 30 times deeper than 2MASS. However, a significant fraction of the sky observed by eROSITA will lack this deeper $K$-band coverage.

Taking advantage of the all-sky coverage of WISE, where the $W1$ is the most sensitive WISE band, and the 35% and 50% sky coverage of SDSS (York et al. 2000) and Pan-STARRS (Kaiser et al. 2010), respectively, we investigate $R \sim W1$ as a diagnostic to uncover obscured supermassive black hole growth in wide-area X-ray surveys. While past studies used $R \sim W2 > 6$ to identify the most obscured AGNs in a sample of W1 – W2-selected objects (Yan et al. 2013; Donoso et al. 2014), here we take a complementary approach by defining AGNs on the basis of their X-ray, rather than infrared, properties, ensuring no contamination from star-forming galaxies in our AGN sample.

Our parent sample is drawn from the Stripe 82X survey, which has a relatively high level of spectroscopic completeness ($\sim$30% for all Stripe 82X sources) compared with all-sky surveys where supporting spectroscopic coverage is inhomogenous. By focusing on objects spectroscopically identified in Stripe 82X, using observed X-ray luminosities to differentiate between AGNs and galaxies without active black holes, we compare $R \sim W1$ with $R \sim K$ to highlight where different classes of objects live in this parameter space. We demonstrate that optically elusive X-ray AGNs beyond the local universe ($z > 0.5$) can be recovered on the basis of their red $R \sim W1$ colors. Additionally, as the Stripe 82X sources are likely to be representative of the objects that are initially discovered in current and future wide-area X-ray surveys prior to follow-up observations, we report on the $R \sim W1$ colors for different observed X-ray luminosity bins. We then compare the mid-infrared-only $W1 \sim W2$ AGN color selection with our X-ray sample to determine which portion of the AGN population is recovered by this color cut. Finally, we test whether inferred X-ray obscuration is associated with optical reddening to determine whether dust that obscures optical light plays a role in attenuating X-ray emission. Throughout the paper, we report $R \sim W1$ and $R \sim K$ colors in the Vega magnitude system and adopt a cosmology where $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Lambda = 0.73$. Additionally, all reported X-ray luminosities represent observed-frame, non-absorption-corrected, full-band (0.5–10 keV)$^{23}$ luminosities.

2. DATA ANALYSIS

2.1. The Stripe 82 X-Ray Sample

Stripe 82X is an ongoing XMM-Newton and Chandra survey of the legacy SDSS Stripe 82 field: in addition to being imaged over 80 times in the optical, with co-added photometry 1.9–2.2 times deeper than any single-epoch SDSS region (Jiang et al. 2014), it has a rich investment of optical spectroscopy from SDSS and SDSS BOSS (Data Releases 9 and 10; Ahn et al. 2012, 2014), 2 SLAQ (Croft et al. 2009), WiggleZ (Drinkwater et al. 2010), DEEP2 (Newman et al. 2013), PRIMUS (Coil et al. 2011), the deep spectroscopic survey of faint quasars from Jiang et al. (2006), and a pre-BOSS pilot survey using Hectospec on MMT (Ross et al. 2012). Furthermore, it has UKIDSS coverage, allowing for deeper near-infrared coverage compared with 2MASS. Archival Chandra and XMM-Newton observations in the field cover $\sim$13.3 deg$^2$, while an additional 4.6 deg$^2$ was obtained from an AO10 XMM-Newton program, resulting in a total of $\sim$16.5 deg$^2$ of non-overlapping area (PI: C. M. Urry; LaMassa et al. 2013a, 2013b); an additional $\sim$15.6 deg$^2$ of Stripe 82X was observed by XMM-Newton in AO13 (PI: C. M. Urry; LaMassa et al. 2015). As a wide-area survey, the X-ray depth is largely shallow, reaching a full-band flux limit of 5.6 x 10$^{-15}$ erg s$^{-1}$ cm$^{-2}$ with a half-area flux limit of 1.6 x 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$, for the initial 16.5 deg$^2$ Stripe 82X release.

$^{23}$ While the XMM-Newton full band ranges from 0.5 to 10 keV, the Chandra full-band coverage is from 0.5 to 7 keV, as Chandra is much less sensitive above 7 keV.
In total, 3362 X-ray sources make up the Stripe 82X sample, detected at the $\geq 5\sigma$ level with XMM-Newton or $\geq 4.5\sigma$ level with Chandra (LaMassa et al. 2013a, 2013b). As described in LaMassa et al. (2013a), the optical and infrared counterparts to the X-ray sources were found using the maximum likelihood estimator, which is a statistical algorithm that accounts for the distance between an X-ray source and multiwavelength objects found within the search radius ($5''$ for Chandra and $7''$ for XMM-Newton), as well as the magnitude distribution of sources in the background and the positional errors on the X-ray and multiwavelength sources (Sutherland & Saunders 1992).

### 2.2. R $- W1$ Sample

Of the 3362 Stripe 82X sources, we focus on the objects that have spectroscopic redshifts so that we can identify the sources and have optical classifications where possible. About 30% of the Stripe 82X sample is spectroscopically complete, leaving 1005 objects, of which 146 were obtained from our dedicated follow-up campaign with WIYN HYDRA and Palomar DoubleSpec from 2012 to 2014. Although many sources for which we have optical spectroscopic redshifts from existing surveys were targeted based on their optical properties, we have made no such a priori cuts on our candidate lists for our follow-up observations so that we achieve as fair a sampling of the X-ray population as possible: we have an ongoing spectroscopic campaign to target every X-ray source that has an optical counterpart. Though limiting our sample to sources that have existing spectroscopic redshifts imposes a bias based on optical properties, the AGN demographics will be representative of those objects immediately identified in current and future wide-area X-ray surveys as these surveys will also be affected by limited spectroscopic completeness.

We then impose an optical magnitude cut of $r \leq 22.2$ (AB) and $i \leq 21.3$ (AB), which represents the 95% completeness limit for point sources in the single-epoch SDSS catalog, garnering 878 objects. From this sample, we then retain objects matched to WISE that have significant W1 detections ($S/N > 5$) and WISE coordinates within $3''$ of the SDSS coordinates: as the multiwavelength counterparts were matched to the X-ray source list independently in LaMassa et al. (2013a), this additional positional cut mitigates unrelated associations between the SDSS and WISE sources. Thus, as summarized in Table 1, our $R - W1$ sample contains 661 objects; 76 of these were spectroscopically identified by our follow-up campaign.

### 2.2.1. UKIDSS Subsample

In this work, we compare how $R - W1$ relates to $R - K$, an often-used color to identify reddened AGNs. We then define a UKIDSS subsample that has $K$-band detections and UKIDSS coordinates within $2''$ of the SDSS coordinates, where a smaller search radius is used here compared with WISE owing to the smaller point-spread function (PSF) and more precise astrometry of UKIDSS. As noted in Table 1, this subsample contains 552 objects.

## Table 1

| Sample            | Number |
|------------------|--------|
| Stripe 82X All   | 3362   |
| Spectroscopic redshifts | 1005   |
| $r \leq 22.2, i \leq 21.3$ (AB) | 878    |
| WISE counterparts ($R - W1$ sample) | 661    |
| $R - W1$ sample with UKIDSS counterparts | 552    |

## Table 2

| Summary of $R - W1$ Sample and UKIDSS Subsample |
|-----------------------------------------------|
| **Class** | **X-ray Classification** | **Optical Classification** |
| X-ray AGNs ($L_x > 10^{42}$ erg s$^{-1}$) | 612 | 499 |
| X-ray galaxies ($L_x < 10^{42}$ erg s$^{-1}$) | 19 | 406 |
| Obscured AGNs$^a$ | 110 | 19 |
| Obscured AGNs, $\alpha > 0.5$ | 98 | 17 |

### Note.

$^a$ In this context, obscured AGNs have optical spectra classified as "galaxies" and X-ray luminosities exceeding $10^{42}$ erg s$^{-1}$.

### 2.3. Object Classification

SDSS and other optical surveys provide automatic classifications of sources based on their optical spectra, and we have adopted their methodology when characterizing objects observed with our dedicated follow-up campaigns: Type 1 AGNs have at least one broad line (generally, FWHM $> 2000$ km s$^{-1}$) present in their optical spectrum; galaxies are objects that lack any broad lines, but these include narrow-lined AGNs, blazars that have featureless optical spectra, as well as objects without any signatures of accretion in their optical spectra; and stars are sources with absorption or emission features at $z \sim 0$. Based on the optical spectra, 499 of the 661 X-ray objects are Type 1 AGNs, 129 are optical galaxies, 30 are stars, and 3 do not have optical classifications in the ground-based databases we mined.

In this work, we refer to X-ray AGNs as those sources with observed 0.5–10 keV luminosities exceeding $10^{42}$ erg s$^{-1}$, or if the full-band flux is not significant, 0.5–2 keV or 2–10 keV luminosities above $10^{42}$ erg s$^{-1}$.

Star formation processes generally are not energetic enough to produce X-ray emission beyond this limit (e.g., Brandt & Hasinger 2005; Brandt & Alexander 2015), though the extended hot gas halo of passive galaxies can reach higher luminosities at $z > 0.55$ (e.g., Civano et al. 2014). Of the 661 objects in our sample, 612 are X-ray AGNs and 19 are X-ray galaxies, which are also optically classified as galaxies. We caution, however, that the $10^{42}$ erg s$^{-1}$ luminosity cut omits low-luminosity and heavily X-ray obscured AGNs from our sample.

We summarize the optical and X-ray classifications of our $R - W1$ sample and UKIDSS subsample in Table 2.

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24 Though blazars are AGNs, they can be misclassified as "galaxies" by optical classification pipelines owing to their lack of broad lines. Visual inspection of the spectra can correctly identify these sources, which we discuss further in Section 3.3.

25 Seventeen extragalactic X-ray objects have nonsignificant full-band fluxes but significant soft-band (0.5–2 keV) and hard-band (2–10 keV) fluxes. We consider these sources X-ray AGNs if either their soft- or hard-band luminosities exceed $10^{42}$ erg s$^{-1}$.
2.4. Calculating $R - W1$

To develop our diagnostic color selection, we utilize the SDSS “modelMag” magnitude. For point sources, this is a PSF model, while for extended sources it is the better of a de Vaucouleurs profile fit or an exponential profile fit; ∼66% of the 661 sources in our sample have morphologies consistent with a point source. For the remaining 34% of sources with extended photometry, the modelMag may be an unreliable estimate of the total magnitude for Type 1 AGNs, as the AGN point-source flux can contribute significantly to the total emission but be poorly modeled by a de Vaucouleurs or exponential profile fit. To test this effect, we compared the “modelMag” with the “auto” magnitudes reported in the Jiang et al. (2014) co-added catalog, which were measured with SExtractor (Bertin & Arnouts 1996); such “auto” magnitudes are the most reliable for extended photometry. As we show in Figure 1, the difference between the r-band “modelMag” and “auto” magnitudes is generally not significant, and there are no global systematic offsets between the magnitudes of extended Type 1 AGNs and point sources. However, we caution that individual sources could have discrepant “modelMag” magnitudes, and the effective $R - W1$ colors calculated here may not always reflect the true $R - W1$ colors for Type 1 AGNs with extended photometry.

We convert $r$ from SDSS filters in the AB system to the Bessell $R$ bandpass (Bessell 1990) in the Vega system to be consistent with many previous red quasar studies (e.g., Brusa et al. 2005, 2015; Georgakakis et al. 2009; Banerji et al. 2012), following the formulae provided in Blanton & Roweis (2007):

$$R_{\text{AB}} = r - 0.0576 - 0.3718((r - i) - 0.2589)$$

(1)

$$R_{\text{Vega}} = R_{\text{AB}} - 0.21,$$

(2)

where the latter equation converts Bessell $R$ from the AB to the Vega magnitude system. For $W1$, we use the instrumental profile-fit photometry magnitude, “w1mpro,” in the WISE All-Sky Source catalog.

2.5. Spectral Evolution with Redshift

To illustrate how the $R$ and $W1$ bands overlap spectral regions that can provide clues as to the type of object being observed, we use the SWIRE template library of Polletta et al. (2007) to plot the spectra for a Type 1 quasar, a reddened quasar (based on the FIRST red quasar J013435.7–093102, Gregg et al. 2002), and a Seyfert 2 galaxy (Sy2, moderate-luminosity, narrow-line AGN; green double-dot-dashed), and the M82 starburst galaxy (black solid) for $z = 0, 0.5, 1$ (Polletta et al. 2007). The gray shaded regions mark the $R$ and $W1$ passbands. Calculated $R - W1$ colors for each object at the various redshifts are noted in the legend. Red $R - W1 (>4)$ colors are an excellent discriminator between obscured and unobscured accretion beyond the local universe, especially at $z > 1$.

As Figure 3 illustrates, the higher-luminosity AGNs in our sample ($>10^{44}$ erg s$^{-1}$) are predominantly at $z > 1$ (owing to the large-area and shallow flux limit of Stripe 82X), such that $R - W1$ is an excellent discriminator between the obscured and unobscured quasar population. We note, however, that nonactive galaxies also become redder as redshift increases, meaning that sources selected based on just $R - W1$ colors
from a parent optical or infrared sample will include a nonnegligible fraction of nonactive galaxies. X-ray emission then becomes an essential clue for separating AGNs from galaxies hosting dormant black holes.

Our focus is then on how the X-ray, optical, and infrared data can be combined to open a new window into obscured black hole growth by examining the \( R_W \) colors of X-ray-selected sources to identify potentially obscured AGNs. In addition to current wide-area X-ray surveys like Stripe 82X, XMM-XXL, and the XMM-Serendipitous Survey, eROSITA will launch in 2017 (Predehl et al. 2014), surveying the full sky from 0.3 to 10 keV with an angular resolution of <15" on-axis, and will detect millions of AGN candidates (Merloni et al. 2012). Though the results here may not be applicable to optically selected or infrared-selected samples, or objects found in very deep X-ray surveys, and the Stripe 82X sample is not complete (i.e., only ~59% of the X-ray objects with SDSS and WISE counterparts within the magnitude limits discussed in Section 2.2 are currently identified via spectroscopic redshifts), the trends we report below are likely to represent the AGN demographics of the sources initially discovered in current and future shallow X-ray surveys, where \( R_W \) can easily be calculated over most of the sky thanks to existing facilities like WISE and Pan-STARRS.

3. RESULTS

3.1. \( R - W_1 \) Sample

In Figure 5 (top), we plot the \( R - W_1 \) distribution of the 631 extragalactic Stripe 82X sources in our sample, highlighting broad-lined AGNs; obscured AGNs, which are categorized as “galaxies” based on their optical spectra but have X-ray luminosities consistent with accretion onto a supermassive black hole; and galaxies, which have both optical signatures and X-ray luminosities consistent with nonactive galaxies. We
also highlight in Figure 5 (top) the subset of obscured AGNs at $z > 0.5$, which is the redshift range where BPT diagnostics using H$\alpha$ and [N II] become unfeasible for observed-frame optical spectra (see Section 3.3 for more discussion); most of these obscured AGNs have red $R - W1 (> 4)$ colors. We note that while a majority of this Stripe 82X sample consists of broad-lined AGNs, they have a range of $R - W1$ colors, rather than being predominantly blue, indicating the presence of a significant fraction of reddened quasars in our sample.

In Figure 5, we compare the $R - W1$ distribution of the Stripe 82X sources lacking spectroscopic redshifts, but meeting the SDSS magnitude and W1 S/N and positional cuts detailed above, with the spectroscopic $R - W1$ sample considered in this work. The X-ray sources without spectra are systematically redder than the objects identified thus far, implying that there are obscured supermassive black holes at $z > 0.5$ in Stripe 82X yet to be confirmed.

3.2. Differentiating Galactic from Extragalactic Objects

Figure 6 shows that $R - W1$ is well correlated with $R - K$ for the subset of our sample that have W1 and K detections. Stars generally follow a well-defined track in $R - K$ versus $R - W1$ color space (top right panel of Figure 6). There is one obvious stellar outlier at $R - W1 > 6$, which is an M dwarf detected by our Palomar DoubleSpec follow-up observing campaign (see Figure 7); however, we note that other M dwarfs follow the stellar sequence. We fit the relation between $R - W1$ and $R - K$ for the stars, omitting the one extreme outlier, finding

$$R - W1 = 0.998(±0.02) \times (R - K) + 0.18,$$

with a correlation coefficient of 0.997. This relationship, overplotted in Figure 6, can be used to distinguish between Galactic and extragalactic X-ray sources in the absence of spectroscopic data or when significant WISE W3 detections are lacking, causing identifications based on the WISE color diagnostic plot (i.e., $W1 - W2$ versus $W2 - W3$; Wright et al. 2010) to be unfeasible. Additionally, this trend provides a more effective method for targeting specific classes of objects in follow-up campaigns over using a simple $R - K$ or $R - W1$ color cut, should K-band coverage be available.

3.3. Optical Galaxies

In our sample, objects spectroscopically classified as galaxies are sources that lack broad emission lines. These objects can be obscured AGNs (either narrow-lined sources or objects where host galaxy dilution obliterates weak signatures of supermassive black hole accretion), blazars that have featureless optical spectra, or galaxies hosting dormant black holes. Since X-rays pierce through the dust that attenuates optical emission and do not suffer dilution effects, such emission cleanly separates active from inactive galaxies when the X-ray luminosity exceeds $10^{42}$ erg s$^{-1}$ (e.g., Brandt & Hasinger 2005; Brandt & Alexander 2015). In the bottom left panel of Figure 6, we use the X-ray emission to split the optical galaxy sample into AGNs ($L_x > 10^{42}$ erg s$^{-1}$) and normal galaxies ($L_x < 10^{42}$ erg s$^{-1}$); we caution, however, that the “normal galaxies” in this subsample can include heavily obscured AGNs, where the observed X-ray emission is severely extinguished by Compton-thick levels of obscuration, or low-luminosity AGNs.

While non-broad-lined AGNs have a range of colors, normal galaxies tend to have bluer colors ($R - W1 < 4$). The latter effect is mostly induced by the flux-limited nature of our sample: owing to the relatively short exposure times for the majority of the X-ray observations, these galaxies are local, spanning a redshift range of $0.04 < z < 0.51$ where the observed spectrum is bluer than it is at higher redshifts (Figures 2–3; see also Brusa et al. 2010). Beyond $z > 0.5$, most of the AGNs optically classified as galaxies have red colors (Figure 6, bottom right), as expected based on the spectral templates.

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26 Here $L_x$ refers to the full-band luminosity if the full-band X-ray flux is significant. Otherwise, we base the AGN cut on the X-ray luminosity exceeding $10^{42}$ erg s$^{-1}$ in either the soft or hard band.
The redshift was determined. The names indicated in the legend are based on the luminosities consistent with AGNs. The marked transitions indicate how the colors, can be categorized as elusive AGNs, and XBONGs from nonactive galaxies at $z > 0.5$; in deeper X-ray surveys, like the Stripe 82X data does not select optically elusive AGNs (continued from Figure 8). While the objects in the bottom panel has a broader Mg II emission line compared with the other species, SDSS classified these sources as “galaxies.” The object in the third panel is a blazar.

Field South (Giacconi et al. 2001; Xue et al. 2011), a higher fraction of nonactive galaxies are detected at $z > 0.5$ (e.g., Lehmer et al. 2005), which would also have $R - W1 > 4$ colors (see Figures 2–3). We note that this cut on the Stripe 82X data does not select optically elusive AGN/XBONGs exclusively, but also includes reddened broad-lined quasars and a handful of X-ray-emitting stars. Using just $R - W1$, the

Two objects were identified via catalogs released from the PRIMUS survey (Coil et al. 2011), whose spectra are not public.
percentage of stellar contaminants to all active galaxies in this color cut is $\sim$3%; when $R - W1 > 4$ is used in conjunction with $R - K$ and the relationship introduced in Section 3.2, this stellar contamination drops to under 0.9%. None of the nonactive galaxies have $R - W1$ colors exceeding 4.

### 3.4. Trends with Observed X-Ray Luminosity

Here we explore $R - W1$ and $R - K$ colors of the Stripe 82X AGNs for different observed full-band X-ray luminosity bins, to test whether there is an association between optical reddening and observed X-ray emission, though we caution that these subsamples are incomplete. As seen in Figures 13–15, AGNs with different observed X-ray luminosities do occupy various regions of optical–infrared parameter space. The lowest-luminosity AGNs ($10^{42}$ erg s$^{-1} < L_{0.5–10 keV} < 10^{43}$ erg s$^{-1}$) have bluer colors, as expected for Seyfert 2 galaxies at $z \sim 0$ (Figure 2). The color trend shifts noticeably redward at moderate X-ray luminosities ($10^{43}$ erg s$^{-1} < L_{0.5–10 keV} < 10^{44}$ erg s$^{-1}$), where the redshifts of this population extend beyond the local universe; red $R - W1$ and $R - K$ colors here and at higher luminosities indicate obscured accretion. At higher X-ray luminosities ($10^{44}$ erg s$^{-1} < L_{0.5–10 keV} < 10^{45}$ erg s$^{-1}$), the distribution spans a full range of colors. The highest-luminosity AGNs ($L_{0.5–10 keV} > 10^{45}$ erg s$^{-1}$) are instead predominantly blue, but owing to the limited spectroscopic completeness of the sample, it is unclear whether this trend is a selection effect or a physical one (see Section 5).

In Figure 14, we differentiate between sources that have spectroscopic redshifts from optical surveys (red dashed line) and those with redshifts from our follow-up campaign (blue dot-dashed line). We caution that only $\sim$12% of our sample has the latter redshifts, and very few of these fall in the lowest- and highest-luminosity bins ($10^{42}$ erg s$^{-1} < L_{0.5–10 keV} < 10^{43}$ erg s$^{-1}$ and $L_{0.5–10 keV} > 10^{45}$ erg s$^{-1}$, respectively). The AGNs we confirmed from our follow-up work tend to have redder $R - W1$ colors at luminosities $10^{43}$ erg s$^{-1} < L_{0.5–10 keV} < 10^{45}$ erg s$^{-1}$, while AGNs with existing redshifts at the same luminosities have a broader range of colors. Hence, our spectroscopic campaign is recovering obscured quasars not identified by optical surveys since X-ray selection is sensitive to objects made fainter by dust that are thus missed by optical selection.

We quantify the luminosity trends in Figure 15 by fitting a Gaussian to each luminosity bin to determine the mean and spread of the $R - W1$ distributions. We find that the mean...
of the distributions tend to be rather wide. The various luminosity bins have different mean $R - W_1$ values, though the widths of the distributions tend to be rather wide.

$R - W_1$ color varies among the luminosity bins, with values of $3.42 (\sigma=0.38)$, $4.14 (\sigma=0.49)$, $3.92 (\sigma=0.64)$, and $3.28 (\sigma=0.71)$ from the lowest to highest luminosities. However, the distributions are quite wide owing to the large range of colors sampled, suggesting that the differences in average $R - W_1$ color are not statistically significant. Additionally, when dividing the $10^{43} \text{erg s}^{-1} < L_{0.5–10 \mathrm{keV}} < 10^{44} \text{erg s}^{-1}$ and $10^{44} \text{erg s}^{-1} < L_{0.5–10 \mathrm{keV}} < 10^{45} \text{erg s}^{-1}$ subpopulations into finer 0.5 dex luminosity bins, the width of the $R - W_1$ distribution does not change, suggesting that the scatter is not induced by sampling a relatively larger population.

4. DISCUSSION

Taken at face value, our results that moderate-luminosity AGNs have red colors while the highest-luminosity AGNs have bluer colors indicate that the former are obscured while the latter are unobscured. Similar results have been found in past X-ray surveys that used gas column density ($N_H$) as an indicator of obscuration (Ueda et al. 2003; Treister & Urry 2006; Hasinger 2008; Lanzuisi et al. 2013; Merloni et al. 2014; Ueda et al. 2014; Buchner et al. 2015).

However, the bluer colors of the most luminous AGNs seem to be at odds with deeper, smaller-area X-ray surveys. Donley et al. (2012) and Eckart et al. (2010) found a trend between X-ray luminosity and IRAC colors in the ∼2 deg$^2$ COSMOS and Serendipitous Extragalactic X-ray Source Identification surveys, respectively, with redder mid-infrared emission associated with more luminous AGNs. Similarly, using infrared and X-ray data from the 0.3 deg$^2$ Extended Chandra Deep Field South survey (Lehmer et al. 2005; Virani et al. 2006), Cardamone et al. (2008) demonstrated that X-ray luminosity trends with redder infrared emission below 8 μm. However, since both these surveys cover a much smaller area than Stripe 82X, only a handful of the most X-ray-luminous AGNs ($>10^{45} \text{erg s}^{-1}$) are found, while 109 are used in this analysis. Thus, we are able to extend the lever arm of this comparison to higher luminosities than formerly explored, albeit with the caveat that this association only holds for the X-ray sources we have thus far identified with spectroscopic redshifts. Also, the optical–infrared colors we use here sample different portions of the SED than the infrared colors used in the past studies, and we work with observed, non-absorption-corrected luminosities rather than rest-frame, absorption-corrected luminosities, as the previous studies used, since these corrections are uncertain.

There may be a population of $L_{0.5–10 \mathrm{keV}} > 10^{45} \text{erg s}^{-1}$ AGNs from the parent Stripe 82 X-ray source list that are not yet identified since they lack spectroscopic redshifts, or indeed even optical counterparts. For instance, the XMM-COSMOS survey finds that 20% of the $L_X > 10^{44} \text{erg s}^{-1}$ quasar population is obscured (Brusa et al. 2010; Merloni et al. 2014); though fewer of the rare high-luminosity quasars are found in this 2.2 deg$^2$ survey compared with wider-area surveys like Stripe 82X, the X-ray identification rate via spectroscopic and photometric redshifts is near 100%, allowing elusive AGNs to be readily identified. In addition to our optical campaign to increase the spectroscopic completeness of Stripe 82X and the calculation of photometric redshifts via SED fitting, we have a dedicated follow-up near-infrared program to target obscured AGN candidates specifically, some of which lack optical counterparts. Preliminary results from these observing campaigns have revealed several $L_{0.5–10 \mathrm{keV}} \sim 10^{44} – 10^{45} \text{erg s}^{-1}$ quasars that are heavily reddened (S. M. LaMassa et al. 2016, in preparation), but future observations are necessary to test whether this population is significant and surpasses that of the unobscured AGNs we have identified thus far.

4.1. W1 – W2-selected AGNs

$R - W_1$ provides an indication of how much the optical emission in AGNs is attenuated, causing the spectrum to be reddened compared with the blue continuum observed in unobscured sources. How does this compare with AGNs selected on the basis of their mid-infrared colors only? Stern et al. (2012) introduced a $W_1 - W_2 > 0.8$ color cut to select AGNs for $W_2$ magnitudes brighter than 15, calibrated on Spitzer-selected AGNs (Stern et al. 2005) in the COSMOS field. Assef et al. (2013) pushed the $W_1 - W_2$ color cut down to fainter magnitudes in the Boötes field, which has deeper WISE coverage than COSMOS, where they found that $W_1 - W_2 > 0.662 \times \exp(0.232 \times (W_2 - 13.97)^2)$ for $W_2 < 17.11$ has a 90% reliability in selecting AGNs that identified via SED fitting. Here we define $W_1 - W_2$-selected AGNs as sources with $W_1 - W_2 > 0.8$ for $W_2 < 15$ and $W_1 - W_2 > 0.662 \times \exp(0.232 \times (W_2 - 13.97)^2)$ for $15 < W_2 < 17.11$; we restrict our Stripe 82X spectroscopic sample to the sources that have $W_2 S/N \geq 5$ for this analysis, resulting in 621 objects.

In Figure 16, we plot $W_1 - W_2$ versus $W_2$ and highlight where the stars, galaxies ($L_{0.5–10 \mathrm{keV}} < 10^{42} \text{erg s}^{-1}$), and optically elusive AGNs and XBONGs at $z > 0.5$ ($L_{0.5–10 \mathrm{keV}} > 10^{42} \text{erg s}^{-1}$) live in this parameter space. Most of the obscured AGNs, which are selected with an $R - W_1$ color cut, do not populate the $W_1 - W_2$ AGN locus (above the blue dot-dashed line). A similar conclusion was reached by Barmby et al. (2006) and Brusa et al. (2010), who reported that a large fraction of obscured AGNs at $z > 1$ lie outside the Stern et al. (2005) IRAC AGN color track, while the Lacy et al. (2004) IRAC color selections were more likely to recover obscured AGNs. Additionally, Menzel et al. (2015),
found that obscured, host-galaxy-dominated, and optically elusive AGNs in XXL-N do not meet the $W1 - W2$ color cut. Additionally, though stars follow a well-defined track in the $R - K$ versus $R - W1$ parameter space, no clear differentiation between Galactic and extragalactic objects based on $W1 - W2$ color is apparent. While stars generally have $W1 - W2$ colors around zero, so too do some galaxies and obscured AGNs.

Identifying AGNs based on infrared-only colors has the highest reliability at brighter fluxes (e.g., Barmby et al. 2006; Cardamone et al. 2008; Donley et al. 2008, 2012; Eckart et al. 2010; Mendez et al. 2013). As we show in Figure 17, the efficacy of $W1 - W2$ in selecting X-ray-identified AGNs increases with luminosity. While 14% of the lowest-luminosity AGNs ($10^{42} \text{ erg s}^{-1} < L_X < 10^{43} \text{ erg s}^{-1}$) and 35% of the moderate-luminosity AGNs ($10^{43} \text{ erg s}^{-1} < L_{0.5-10 \text{ keV}} < 10^{44} \text{ erg s}^{-1}$) meet the $W1 - W2$ AGN color criterion, this fraction increases appreciably for the moderately high ($10^{44} \text{ erg s}^{-1} < L_{0.5-10 \text{ keV}} < 10^{45} \text{ erg s}^{-1}$) and high-luminosity AGNs ($L_{0.5-10 \text{ keV}} > 10^{45} \text{ erg s}^{-1}$), with 68% and 71% of these populations, respectively, meeting the $W1 - W2$ AGN definition. In total, 55% of the Stripe 82X AGNs meet the $W1 - W2$ AGN color cut. But does this $W1 - W2$ color cut select the obscured portion of the X-ray AGN population?

To answer this, we again plot the distribution of $R - W1$ for the different luminosity bins in Figure 18 and highlight the subset that are classified as AGNs based on their $W1 - W2$ colors. Like the parent X-ray AGN samples, $W1 - W2$ AGNs have a wide range of $R - W1$ values and are not preferentially reddened. While $W1 - W2$ is an efficient and robust diagnostic to select unobscured and obscured AGNs, including Compton-thick AGNs that can be missed altogether by X-ray surveys, additional metrics, such as $R - W1$, are useful in recovering a reddened population missed by this infrared-only cut (Stern et al. 2012; Yan et al. 2013; Donoso et al. 2014).

4.2. Is X-Ray Obscuration Related to Optical Reddening?

A detailed investigation of X-ray obscuration can only be obtained by fitting high-quality X-ray spectra with hundreds to thousands of counts (e.g., Akylas et al. 2006; Tozzi et al. 2006; Mainieri et al. 2007; Lanzuisi et al. 2013; LaMassa et al. 2014). As the requisite signal-to-noise ratio for such an analysis is not available for the majority of sources discovered in X-ray surveys, a simpler diagnostic, the hardness ratio (HR), is often used as a proxy of X-ray extinction (e.g., Kim et al. 2007; Fiore et al. 2008, 2009; Wilkes et al. 2009; Civano et al. 2012). HR is defined as $(H - S)/(H + S)$, where $H$ and $S$ are the net counts in the hard (2–10 keV) and soft (0.5–2 keV) bands, respectively.28 HR as an obscuration diagnostic is redshift dependent, 28 The Chandra hard band is 2–7 keV.
since higher-energy X-ray emission, which is less affected by absorption, is shifted into the observed frame, while any soft excess X-ray emission is shifted out of the observed frame as redshift increases. Additionally, the effective area of the instrument plays a role, with different conversions between both Chandra and XMM-Newton, as well as between the XMM-Newton PN camera and XMM-Newton MOS1 and MOS2 detectors. We illustrate this in Figure 19, where we plot HR as a function of redshift for X-ray column density ($N_{\text{H}}$) values of $10^{21}$, $10^{22}$, and $10^{23}$ cm$^{-2}$ separately for Chandra (thick black line) and the XMM-Newton MOS and PN detectors (thinner blue lines); here we assumed an absorbed power-law model where $\Gamma = 1.8$. The spectral slope of a source also influences the HR, but obscuration affects the shape of the spectrum, so owing to this degeneracy, we do not separately consider the effects of varying the spectral slope. At a fixed redshift, greater HR values correspond to larger column densities (see also Weigel et al. 2015).

To calculate HRs for the Stripe 82X AGNs, we use the Bayesian Estimator of Hardness Ratios (BEHR; Park et al. 2006). This method robustly calculates the HRs and associated errors, even in the low count regime and in cases where a source is undetected in either the hard or soft band. Both the source and background photons are modeled as independent Poisson variables, with posterior distributions obtained by Monte Carlo integration via the Gibbs algorithm. For reference, we have chosen to use the default BEHR values of 10,000 draws, with the number of burn-in draws set to 5000.

The number of source and background photons inputted into BEHR for the XMM-Newton sources was extracted from the co-added PN, MOS1, and MOS2 images. Since the effective exposure times can vary among the detectors, we do not average the theoretical HR values shown in Figure 19, but note that the observed HRs fall within the range depicted. The median HR error bars, ~0.3, span a wider range than the spread in the model XMM-Newton HRs.

Since HR as a proxy of X-ray obscuration is heavily dependent on the redshift of the AGN, we investigate the relationship between HR and $R - W1$ in redshift bins. These bins were chosen to be fine enough so that the implied $N_{\text{H}}$ value does not vary greatly from the lowest to highest redshift in the bin (see Figure 19 for reference), while still being wide enough to include a sufficient number of sources to search for trends. In Figures 20–21, we also plot a dashed line to indicate the Chandra HR that corresponds to $N_{\text{H}} = 10^{22}$ cm$^{-2}$ at the median redshift of the bin; HRs greater than this value correspond to higher column densities. As Figures 20–21 show, no trends exist between optical reddening and X-ray obscuration.
Previous studies of X-ray-selected AGNs have found that reddened AGNs tend to be associated with higher levels of X-ray obscuration, based on their HRs (e.g., Mignoli et al. 2004; Brusa et al. 2005; Fiore et al. 2009; Civano et al. 2012). Though we do not find a global trend between $R - W_1$ and HR, we test whether the redder sources in each redshift bin tend to have higher HRs than the bluer sources. Here we define reddened AGNs as those objects with $R - W_1 > 4$ since unobscured quasars generally do not exceed this value beyond the local universe (see Figures 2–3). As shown in Table 3, the reddest AGNs do not have higher HRs than the bluer AGNs. The apparent dichotomy between our results and those of previous surveys can be largely attributed to the definition of obscured AGNs. The extremely reddened AGNs studied in Mignoli et al. (2004), Brusa et al. (2005), Fiore et al. (2009), and Civano et al. (2012), which are associated with larger amounts of X-ray obscuration, are predominantly narrow-lined AGNs. However, the Stripe 82X AGN sample consists of mostly broad-lined sources, and they are exclusively so at $z > 1.$ Though some of these broad-lined quasars are reddened, their HRs imply that they are not correspondingly X-ray obscured. Since these AGNs are presumably viewed face-on to allow the broad emission lines to be visible, reddening from circumnuclear obscuration would be out of the line of sight. The model we have used here to parameterize the AGN spectrum, assuming a foreground screen of extinction, would then be inappropriate.

Additional complications arise in using HRs as a direct proxy of $N_H$. Many X-ray-obsured AGNs are best described by a partial-covering model, where a fraction of the intrinsic AGN continuum leaks through the circumnuclear obscuration, enhancing emission at soft energies (e.g., LaMassa et al. 2009; Turner & Miller 2009; Winter et al. 2009; Mayo & Lawrence 2013). HRs derived via a simple absorbed power-law model, where higher values of $N_H$ are associated with attenuated soft X-ray emission, would then underestimate the column density. Another possibility is that some of these reddened AGNs may have ionized, instead of neutral, gas, which would also boost the soft X-ray emission (e.g., Turner et al. 1991; Krolik & Koss 1995). However, these effects decrease with redshift as the rest-frame soft band becomes shifted out of the observed frame, yet we do not see that the reddened AGNs in Stripe 82X at higher redshift are associated with higher amounts of implied X-ray obscuration. Finally, we note that while synchrotron emission from jets can cause red $R - W_1$ colors (e.g., Massaro et al. 2011), only 32 of these AGNs have a radio counterpart, half of which have bluer colors ($R - W_1 < 4$), suggesting that optical obscuration is responsible for the observed reddening for the majority of the $R - W_1 > 4$ sources.

| HR | [0.25 < z < 1.25] | [0.6 < z < 818] |
|----|-----------------|-----------------|
| $R - W_1 > 4$ | 0.12 ± 0.38 | -0.46 ± 0.26 |
| $R - W_1 < 4$ | -0.18 ± 0.56 | -0.50 ± 0.21 |
| $R - W_1 > 4$ | -0.32 ± 0.49 | -0.42 ± 0.27 |
| $R - W_1 < 4$ | -0.27 ± 0.46 | -0.49 ± 0.23 |
| $R - W_1 > 4$ | -0.44 ± 0.35 | -0.45 ± 0.32 |
| $R - W_1 < 4$ | -0.50 ± 0.34 | -0.46 ± 0.25 |
| $R - W_1 > 4$ | -0.38 ± 0.38 | -0.41 ± 0.32 |
| $R - W_1 < 4$ | -0.60 ± 0.24 | -0.46 ± 0.33 |

5. CONCLUSIONS

Using the 661 Chandra and XMM-Newton sources from the initial ~16.5 deg$^2$ release of the Stripe 82X survey that have SDSS counterparts, significant WISE W1 detections (S/N $> 5$), and spectroscopic redshifts (LaMassa et al. 2013a, 2013b), we investigated $R - W_1$ as a diagnostic to uncover obscured AGN candidates in wide-area X-ray surveys. We focused on observed quantities to explore the parameter space in which different classes of objects live. $R - W_1$ is well correlated with $R - K$, an oft-used reddened AGN selection criterion (e.g., Brusa et al. 2005; Glikman et al. 2007, 2012, 2013; Georgakakis et al. 2009; Banerji et al. 2012, 2015), and is thus helpful in such searches where $K$-band coverage deeper than 2MASS is lacking. Though $R - W_1$ identifies AGNs similar to those selected based on $R - K$ and $R - [3.6] \mu$m colors, the full-sky coverage of WISE, 35% sky coverage of SDSS, and 50% sky coverage of Pan-STARRs make $R - W_1$ a particularly suitable diagnostic to identify interesting AGN candidates for spectroscopic follow-up over a much larger area of the sky. The preexisting availability of $R - W_1$ is of particular relevance for current wide-area X-ray surveys, as well as the upcoming all-sky eROSITA X-ray survey, and will thus recover AGNs missed via alternative selection criteria, helping to complete the census of supermassive black hole growth.

Our main results pertaining to the utility of $R - W_1$ as an AGN color selection, as well as the relationships between $R - W_1$ and additional multiwavelength information, are summarized below:

1. Most stars occupy a distinct track in $R - K$ versus $R - W_1$ parameter space, following the relation $R - W_1 = 0.998(\pm 0.002) \times (R - K) + 0.18$ (Figure 6, top right). A combination of optical, mid-infrared, and near-infrared colors can then be used to identify stars with high confidence in X-ray samples in the absence of spectroscopic data or to more precisely target extragalactic (or Galactic) sources when undertaking follow-up spectroscopic campaigns. This selection criterion will lead to cleaner samples than employing a simple $R - K$ color cut, and it is useful when W3-band detections are lacking, making the WISE $W_1$ versus $W_2$ color diagnostic (Wright et al. 2010) untenable.

2. At redshifts above 0.5, optically normal galaxies hosting AGNs (objects lacking broad spectral lines but having X-ray luminosities exceeding $10^{42}$ erg s$^{-1}$) typically have red $R - W_1$ colors (Figure 6, bottom right). Most of these moderate- to moderately high luminosity AGNs ($10^{43}$ erg s$^{-1} < L_{0.5-10keV} < 10^{45}$ erg s$^{-1}$) are optically elusive AGNs (having narrow emission lines consistent with star-forming galaxies or LINERs) or XBONGs (with optical spectra of passive galaxies, lacking emission lines). We suggest that a color cut of $R - W_1 > 4$ in X-ray samples from shallow surveys separates these
elusive AGNs at redshifts $0.5 < z < 1$ from galaxies hosting dormant black holes at $z < 0.5$. Based on the Stripe 82X sample, the stellar contamination above $R - W1 > 4$ is $\sim 3\%$, but drops to under 0.9% when using $R - W1 > 4$ in tandem with $R - K$ and the relationship derived above to remove objects in the stellar locus.

3. We find that the $W1 - W2$ color cut to select AGNs from Stern et al. (2012) and Assel et al. (2013) more efficiently identifies the high-luminosity AGNs ($L_{0.5-10keV} > 10^{44} \text{ erg s}^{-1}$), while most of the AGNs below these luminosities are not within the $W1 - W2$ AGN locus (Figure 17). Additionally, $W1 - W2$-selected AGNs have a range of $R - W1$ colors (Figure 17), demonstrating that this diagnostic selects both unobscured and obscured AGNs; $R - W1$ can then recover portions of the reddened AGN population not selected via $W1 - W2$. Optically elusive AGNs generally are not within the $W1 - W2$ AGN locus.

4. No clear trend exists between implied X-ray obscuration (parameterized by the X-ray HR) and $R - W1$ (Figures 20–21). This lack of correlation likely results from the fact that many of the Stripe 82X AGNs are broad-lined objects, where circumnuclear obscuration affecting X-ray emission is presumably occurring out of the line of sight and HRs as a proxy for $N_H$ are of limited utility when the X-ray spectra are complex. Though our results are affected by incompleteness, it seems clear that an AGN can be dust reddened without being correspondingly X-ray obscured along the line of sight.

Additionally, we explored the $R - W1$ colors for different observed X-ray luminosity bins (Figures 14–15). Though these trends may change when a higher percentage of X-ray sources are identified with spectroscopic and photometric redshifts, these findings are likely to represent the AGN demographics of sources initially identified in future wide-area X-ray surveys, including eROSITA, since these samples will have similar, or lower, spectroscopic completeness:

1. The lowest and highest X-ray luminosity bins ($10^{42} \text{ erg s}^{-1} < L_{0.5-10keV} < 10^{44} \text{ erg s}^{-1}$) predominantly have bluer $R - W1$ colors. While the lowest-luminosity AGNs are in the local universe, where $R - W1$ is not an indicator of obscuration, the blue $R - W1$ colors of the highest-luminosity AGNs in the sample cleanly demonstrate that this population is unobscured.

2. Moderate-luminosity AGNs ($10^{43} \text{ erg s}^{-1} < L_{0.5-10keV} < 10^{44} \text{ erg s}^{-1}$) tend to have redder $R - W1$ colors, while moderately high luminosity AGNs ($10^{42} \text{ erg s}^{-1} < L_{0.5-10keV} < 10^{45} \text{ erg s}^{-1}$) span the widest range of $R - W1$ colors. In the latter luminosity bin, AGNs identified by our ground-based campaign largely represent the red (i.e., obscured) portion of the population.

These trends are only tested on the Stripe 82X sources that we are able to identify via spectroscopic redshifts, which is currently $\sim 59\%$ of the X-ray sources with SDSS counterparts within the magnitude limits of $r < 22.2$ and $i < 21.3$ and W1-band detections at the $5\sigma$ level. There may exist a population of heavily reddened, luminous AGNs in our sample that may be revealed after additional spectroscopic follow-up. Indeed, the most obscured population may not be detected in optical surveys and would by definition be omitted from this sample. We are executing a ground-based near-infrared campaign to target this class of objects and have discovered several $L_{0.5-10keV} > 10^{44} - 10^{45} \text{ erg s}^{-1}$ quasars that are heavily reddened (LaMassa et al. 2016, in preparation). Future spectroscopic follow-up will reveal whether such high-luminosity obscured black hole growth is significant.

Finally, we re-emphasize that the relationships and trends reported here pertain to X-ray sources. For instance, non-X-ray-emitting stars could populate a much larger range in the $R - K$ versus $R - W1$ parameter space. Dusty star-forming galaxies and (ultra)luminous infrared galaxies have red $R - W1$ colors, but do not necessarily host accreting supermassive black holes. Additionally, as Stripe 82X has relatively high X-ray flux limits, the normal galaxies detected are in the nearby universe: deep surveys, like the Chandra Deep Field South (Giacconi et al. 2001; Xue et al. 2011), uncover normal galaxies much farther away (Lehmer et al. 2012), which could potentially have colors as red as the Stripe 82X XBONGs and optically elusive galaxies between $0.5 < z < 1$. The results here are instructive in informing follow-up for the many current and planned wide-area, shallow X-ray surveys by developing focused selection criteria for specific classes of interesting objects (e.g., X-ray-emitting stars, XBONGs, red quasars) that can be discovered via the power of combining X-ray, infrared, and optical coverage.

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