DISCOVERY OF A POPULATION OF BULGELESS GALAXIES WITH EXTREMELY RED MID-IR COLORS: OBSCURED AGN ACTIVITY IN THE LOW-MASS REGIME?

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ABSTRACT

In contrast to massive, bulge hosting galaxies, very few supermassive black holes (SMBHs) are known in either low-mass or bulgeless galaxies. Such a population could provide clues to the origins of SMBHs and to secular pathways for their growth. Using the all-sky Wide-field Infrared Survey Explorer (WISE) survey, and bulge-to-disk decompositions from the Sloan Digital Sky Survey (SDSS) Data Release 7, we report the discovery of a population of local ($z < 0.3$) bulgeless disk galaxies with extremely red mid-infrared colors which are highly suggestive of a dominant active galactic nucleus (AGN), despite having no optical AGN signatures in their SDSS spectra. Using various mid-infrared selection criteria from the literature, there are between 30 and over 300 bulgeless galaxies with possible AGNs. Other known scenarios that can heat the dust to high temperatures do not appear to explain the observed colors of this sample. If these galaxies are confirmed to host AGNs, this study will provide a breakthrough in characterizing the properties of SMBHs in the low bulge mass regime and in understanding their relation with their host galaxies. Mid-infrared selection identifies AGNs that dominate their host galaxy’s emission and therefore reveal a different AGN population than that uncovered by optical studies. We find that the fraction of all galaxies identified as candidate AGNs by WISE is highest at lower stellar masses and drops dramatically in higher mass galaxies, striking contrast to the findings from optical studies.

Key words: black hole physics – galaxies: active – galaxies: spiral – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

It is now well-established that supermassive black holes (SMBHs) $\sim 10^6$–$10^9 M_\odot$ reside in the centers of bulge-dominated galaxies in the local universe and that their black hole masses and host galaxy bulge mass are strongly correlated (e.g., Gebhardt et al. 2001; Ferrarese & Merritt 2000). These observations have formed the basis of the widely held view that galaxies and their central black holes are fundamentally linked, a link that can most simply be understood if galaxy mergers induce bulge growth and feed the central black hole in concert (e.g., Kauffmann et al. 2003; Ellison et al. 2011). While the SMBH and host galaxy properties in the high bulge mass regime have been studied extensively, very little is known about the existence and properties of SMBHs in galaxies with low masses and/or those with small bulges. This is a significant deficiency since the study of this population allows us to gain an understanding of merger-free pathways to black hole growth. Furthermore, the occupation fraction and properties of SMBHs in low-mass bulgeless galaxies provide one of the only observational constraints on the origin and efficiency of SMBH seeds thought to have formed at high $z$ (e.g., Volonteri 2010). Since SMBHs in massive-bulge-dominated galaxies have undergone significant accretion through multiple dynamical interactions over cosmic history, any information on the seed population will not be retained. In contrast, low-mass galaxies that lack significant bulges have undergone a more secular evolution and therefore the mass distribution and occupation fraction of SMBHs in these galaxies contains clues about the original seed population, allowing us to discriminate between lower mass seeds formed from stellar remnants and massive seeds formed directly out of dense gas (e.g., van Wassenhove et al. 2010). The study of black holes at the low bulge mass regime is therefore crucial to our understanding of both the origin of SMBHs and their growth and connection to galaxy evolution.

Unfortunately, finding and studying the properties of SMBHs in a significant sample of galaxies with low bulge mass is challenging since the black hole mass is expected to be small and therefore impossible to discover dynamically, except in the few nearest galaxies. A significant sample of SMBHs in low-mass hosts can therefore only be detected if they are accreting. On the basis of optical spectroscopic observations, active galactic nuclei (AGNs) are found almost exclusively in massive bulge-dominated hosts, with the fraction of galaxies with optical signs of accretion dropping dramatically at stellar masses $\log(M/M_\odot) < 10$ (e.g., Kauffmann et al. 2003). One possible reason for this deficit of AGNs at low galaxy mass is that a putative AGN in a galaxy with a minimal bulge is likely to be both energetically weak and possibly deeply embedded in the center of a dusty late-type galaxy. As a result, the optical emission lines may be dominated by star formation regions and/or considerably attenuated by dust. This leaves open the possibility that there is a hidden population of accreting black holes in small-bulge systems. To date, only small samples of AGNs discovered by optical surveys in small-bulge galaxies exist and far fewer with no evidence of any bulge (e.g., Filippenko & Ho 2003; Barth et al. 2004; Greene & Ho 2007; Jiang et al. 2011; Simmons et al. 2013; Coelho et al. 2013).

Despite several X-ray and infrared studies aimed at searching for AGNs in the low bulge mass regime (e.g., Satyapal et al. 2007, 2008, 2009; Gliozzi et al. 2009; McAlpine et al. 2011; Secrest et al. 2012; Shields et al. 2008; Ghosh et al. 2008; Jiang et al. 2011; Simmons et al. 2013; Gliozzi et al. 2009; McAlpine et al. 2011; Secrest et al. 2012; Shields et al. 2008; Ghosh et al. 2008; Satyapal et al. 2007, 2008, 2009; Gliozzi et al. 2009; McAlpine et al. 2011; Secrest et al. 2012; Shields et al. 2008; Ghosh et al. 2008;
Dewangan et al. 2005; Desroches & Ho 2009; Reines et al. 2011; Araya Salvo et al. 2012), there are still only a small number of purely bulgeless galaxies with evidence for SMBHs known in the universe. Interestingly, several of the nearby bulgeless disk galaxies with high spatial resolution observations show evidence for prominent nuclear star clusters (NSCs) possibly suggesting an association of SMBHs and NSCs in the complete absence of a bulge (Satyapal et al. 2009; Secrest et al. 2013). In contrast, the dwarf galaxy He 2–10 shows no evidence of an NSC but shows a clear signature of an SMBH as well as clear signs of a recent interaction (Reines et al. 2011). With only a few examples, it is impossible to address important questions such as: Why do some completely bulgeless disk galaxies have AGNs and some do not? Are the presence and properties of the central black hole related in any way to the properties of the host galaxies in galaxies with truly no bulge? What is the relationship between NSCs and SMBHs? What is the occupation fraction of SMBHs in truly bulgeless galaxies? A statistically significant sample of low bulge and bulgeless galaxies with confirmed SMBHs is needed in order to make significant progress in the study of SMBH formation, growth and the connection with galaxy evolution.

Since AGNs in bulgeless galaxies are very rare, it is impossible to find a sizeable sample of such objects by carrying out X-ray or mid-infrared spectroscopic observations of small samples of bulgeless galaxies. The all-sky survey carried out by the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) has opened up a new window in the search for optically hidden AGNs in a large number of galaxies based on their characteristically very red mid-infrared colors (Stern et al. 2012). In this paper, we report the discovery of a population of nearby bulgeless galaxies discovered by WISE to have extreme red mid-infrared colors indicative of hot dust, usually thought to be heated by AGNs. In Section 2, we describe the selection of our bulgeless galaxy sample, followed by a discussion of their WISE colors in Section 3. In Section 4, we describe the properties of the subset of bulgeless galaxies in the sample identified by WISE with red mid-IR colors suggestive of AGNs. In Section 5, we discuss alternative scenarios that can produce red mid-IR colors in galaxies., followed by a discussion of supporting multi-wavelength evidence for AGNs in bulgeless and low-mass galaxies. In Section 7, we explore the dependence of WISE AGN selection on stellar mass for the full range of stellar masses, followed by a summary and implications of our results in Section 8.

2. BULGELESS GALAXY SAMPLE

Our sample of bulgeless galaxies is drawn from the catalog of bulge/disk decompositions of 1.12 million galaxies from the Sloan Digital Sky Survey (SDSS) Data Release 7 from Simard et al. (2011). Here, two dimensional, point spread function convolved, bulge–disk decompositions are performed in both the r and g bands using three different galaxy fitting models: a pure Sérsic model, a bulge + disk model, and a Sérsic with free index bulge + disk model (see Simard et al. 2011 for details). We chose to construct the most conservative sample of bulgeless galaxies identified by this catalog by requiring a bulge-to-total (B/T) ratio of 0 in both the r and g bands for the best-fit model. We also required that SDSS spectroscopic data were available for all galaxies so that the redshifts of the sample were determined. We cross-matched this SDSS bulgeless galaxy sample with the final WISE all-sky data release catalog

4 http://wise2.ipac.caltech.edu/docs/release/allsky/

5 http://www.mpa-garching.mpg.de/SDSS/
Second, it is important to consider whether any of the galaxies in the sample are interacting in order to determine if the galaxies are “pristine,” with SMBHs that have evolved secularly over cosmic time. We investigated the merger status of the galaxies in our sample using the Galaxy Zoo project.\(^6\) Galaxy Zoo users were asked to identify morphological signs of interactions by selecting a “merger” button. Of the 13,862 galaxies in our bulgeless galaxy sample, 13,060 had Galaxy Zoo classifications available. We used the weighted-merger-vote-fraction, \(f_m\), to explore the interaction status of the sample. This parameter varies from 0 to 1, where 0 represents a clearly isolated galaxy and a value of 1 represents a definitive merger (for details, see Darg et al. 2010). Based on an investigation of the Galaxy Zoo catalog, Darg et al. find that \(f_m > 0.6\) robustly identifies mergers. For \(f_m < 0.4\), misclassifications occur based on the projection of galaxies and stars along the line of sight as well as cases where the galaxy hosts may appear disturbed but there are no visual signs of a companion. In the entire bulgeless sample with Galaxy Zoo classifications, 12,855 (98%) have \(f_m < 0.4\), 12,135 (93%) have \(f_m < 0.1\), and 9176 (70%) have \(f_m = 0\), indicating a high probability that they are isolated galaxies. Although the aforementioned cautions apply to the selection of bulgeless AGNs with close companions (i.e., in terms of their genesis and potential selection issues), we have not explicitly excluded these from our sample, as they may still be interesting for future study. However, we emphasize that the vast majority of bulgeless galaxies appear to be isolated bulgeless galaxies based on SDSS data.

3. MID-IR COLORS OF BULGEOSS GALAXIES AND WISE AGN SELECTION CRITERIA

Extensive efforts over the past decade have demonstrated the power and reliability of mid-infrared observations in discovering optically hidden AGNs. This is thought to be because hot dust surrounding AGNs produces a strong mid-infrared continuum and infrared spectral energy distribution that is clearly distinguishable from normal star-forming galaxies for both obscured and unobscured AGNs in galaxies where the emission from the AGN dominates over the host galaxy emission (e.g., Stern et al. 2012). In particular, at low redshift, the \(W_1 - W_2\) color of galaxies dominated by AGNs is considerably redder than that of inactive galaxies (see Figure 1 in Stern et al. 2012; Assef et al. 2013). At higher redshifts (\(z > 1.5\)) the host galaxy becomes red across these bands but becomes undetectable by WISE.

There are several WISE color diagnostics that have been employed in the literature to select AGNs. Based on the Spitzer–WISE ecliptic pole data, which contains the highest coverage depths achieved by WISE, Jarrett et al. (2011) define an “AGN” region in \(W_1 - W_2\) versus \(W_2 - W_3\) color–color space using the first 3 WISE bands that separates AGNs that dominate over their host galaxies from normal galaxies. Using the shallower COSMOS data, Stern et al. (2012) show that while inclusion of the longer wavelength bands increases the reliability of AGN selection due to contamination from high redshift (\(z > 1.3\)) galaxies, for low redshifts, WISE is able to robustly identify AGNs using the more sensitive \(W_1\) and \(W_2\) bands alone. Donley et al. (2012), using a combination of galaxy templates and real data from pure starbursts identified from Spitzer IRS spectroscopy, demonstrate that this mid-infrared color selection has minimal contamination from purely star-forming galaxies that are below a redshift of \(z \sim 1\). Using the IRAC-selected AGN as their “truth sample” Stern et al. (2012) show that color cuts of \(W_1 - W_2 > 0.8\), \(W_1 - W_2 > 0.7\), \(W_1 - W_2 > 0.6\), and \(W_1 - W_2 > 0.5\) identify IRAC AGNs with a reliability of 95%, 85%, 70%, and 50%, respectively. However, they point out that these numbers are conservative, since it is unknown whether or not the “non-AGN” contaminants are truly active. In fact, they show that some of the contaminants with spectroscopic redshifts available are indeed confirmed to be broad-line quasars. Given that the redshifts of the galaxies in our sample are low, and that WISE color selections are critically sensitive to the AGN’s power relative to that of the host galaxy, we explore a range of these published color cuts in our bulgeless sample.

In Figure 1, we plot the \(W_1 - W_2\) versus \(W_2 - W_3\) color for the galaxies in our bulgeless sample alongside those from a few purely bulgeless galaxies with AGNs from the literature as well as those from the sample of broad line AGNs with low-mass black holes from Greene & Ho (2007). The AGN region from Jarrett et al. (2011) is shown together with the \(W_1 - W_2 > 0.8\) (red dashed line) and \(W_1 - W_2 > 0.5\) (blue dashed line) color cuts. Several known bulgeless galaxies with confirmed AGNs are highlighted along with those from the sample of low-mass optically identified broad line AGNs from Greene & Ho (2007).

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

\(^6\) http://www.galaxyzoo.org

\[ \text{Figure 1.} \quad W_1 - W_2 \text{ color vs. the } W_2 - W_3 \text{ color of our bulgeless galaxy sample. The AGN region from Jarrett et al. (2011) is shown together with the } W_1 - W_2 > 0.8 \text{ (red dashed line) and } W_1 - W_2 > 0.5 \text{ (blue dashed line) color cuts. Several known bulgeless galaxies with confirmed AGNs are highlighted along with those from the sample of low-mass optically identified broad line AGNs from Greene & Ho (2007).} \]
### Table 1

| SDSS Name | W1 − W2 (mag) | log(M/M☉) | z |
|-----------|----------------|------------|---|
| J012118.11+010025.8 | 1.60 | 10.0 | 0.055 |
| J131851.34+340124.9 | 1.52 | 10.0 | 0.056 |
| J160361.87+022144 | 1.30 | 10.5 | 0.050 |
| J155409.80+145703.5 | 1.14 | 10.9 | 0.173 |
| J142231.37+262025 | 1.11 | 10.7 | 0.159 |
| J122343.66+555522.3 | 1.10 | 10.3 | 0.052 |
| J105430.96+292845.7 | 1.00 | 10.4 | 0.147 |
| J123304.57+023471.7 | 0.98 | 10.0 | 0.069 |
| J143464.55+24715.8 | 0.97 | 11.3 | 0.221 |
| J112824.27+115615.2 | 0.94 | 10.4 | 0.162 |
| J142847.54+324436.8 | 0.93 | 10.8 | 0.195 |
| J232020.09+150420.5 | 0.91 | 10.6 | 0.148 |
| J130131.53+212748.7 | 0.91 | 10.1 | 0.087 |
| J093333.86+100717.1 | 0.87 | 10.7 | 0.178 |
| J092907.76+002637.2 | 0.85 | 11.0 | 0.117 |
| J103549.57+122406.7 | 0.84 | 0.146 |
| J132932.41+323417.0 | 0.82 | 10.2 | 0.120 |
| J133502.41+082220.9 | 0.81 | 11.3 | 0.267 |
| J085121.74+094010.2 | 0.81 | 10.5 | 0.112 |
| J114753.62+049551.9 | 0.81 | 10.3 | 0.095 |
| J140515.45+581247.3 | 0.77 | 11.3 | 0.250 |
| J085236.35+292852.3 | 0.76 | 10.2 | 0.079 |
| J103222.94+361727.8 | 0.74 | 10.9 | 0.236 |
| J155448.29+090817.9 | 0.74 | 10.9 | 0.166 |
| J133431.72+656316.1 | 0.73 | 10.9 | 0.158 |
| J132647.54+101436.4 | 0.73 | 10.3 | 0.089 |
| J122809.2+581431.5 | 0.72 | 10.5 | 0.110 |
| J085153.64+392611.8 | 0.71 | 10.6 | 0.130 |
| J124820.31+183545.2 | 0.71 | 10.8 | 0.110 |

**Note:** a Optically identified AGNs.

and He 2–10, all discovered recently to host AGNs, all have W1 − W2 colors below those of any of the color cuts adopted in this work since the AGNs are weak compared to the host galaxy. Even within the sample from Greene & Ho, which are all indisputable broad line AGNs, 72% have W1 − W2 < 0.8, and 36% have W1 − W2 < 0.5.

Since the redshifts of our bulgeless galaxy sample are low, well below the threshold at which high redshift contaminants are a concern, and all of the color cuts shown in Figure 1 identify AGNs that dominate over their host galaxy emission, it is possible that a significant fraction of the bulgeless galaxies with W1 − W2 > 0.5 do indeed host AGNs, and therefore these galaxies should be investigated with follow-up multi-wavelength observations.

### 4. PROPERTIES OF BULGELESS WISE-IDENTIFIED AGN CANDIDATES

In Table 1, we list the WISE W1 − W2 colors, masses, and redshifts of the bulgeless galaxies that meet the most stringent three-band color cut from Jarrett et al. (2011). These are the AGN candidates most likely to contain dominant AGNs based on their mid-infrared colors. All galaxies are nearby, with redshifts ranging from 0.016 to 0.27, with a mean redshift of 0.13. The masses of the galaxies range from log(M/M☉) = 8.1 to 11.3, with a mean of 10.5.

In Figure 2, we display the SDSS images of these AGN candidates organized by decreasing W1 − W2 color, as listed in Table 1. The morphologies of the WISE AGN hosts range from low surface brightness objects with little structure to more structured bulgeless disks, and some are clearly interacting galaxies. Galaxies with optical line ratios consistent with AGNs are indicated in the images. The majority of WISE-identified AGN candidates in Table 1 show no signatures of an AGN based on their optical spectra, suggesting that this population is obscured in the optical. In Figure 3, we plot the optical BPT diagram for all galaxies in our bulgeless galaxy sample with the optical emission line fluxes detected above the 3σ level. Galaxies with WISE colors consistent with AGNs based on the various WISE color cuts are highlighted. Of the 25 galaxies that meet the W1 − W2 > 0.8 color cut, only 2 have optical line ratios that are above the Kewley et al. (2001) AGN region of the BPT region. Only 4% of the galaxies that have W1 − W2 > 0.5 are in the Kewley et al. (2001) AGN region of the BPT diagram. In a complementary analysis exploring black hole scaling relations, Marleau et al. (2013) have also identified a population of WISE AGNs and explored their distribution of bulge and disk masses.

### 5. ALTERNATIVE SCENARIOS AND CAVEATS

While the red mid-infrared color of the bulgeless galaxies presented in this work is highly suggestive of AGN activity, it is possible that the red colors are due solely to star formation. For example, ultraluminous infrared galaxies (ULIRGs) can have W1 − W2 colors that are well in excess of 1 (e.g., Jarrett et al. 2011; Yan et al. 2013), though these red colors may indeed be due to AGN activity since many if not most ULIRGs host obscured AGNs (e.g., Veilleux et al. 2009). We searched for IRAS detections for the bulgeless AGN candidates. Only 5 of the 30 galaxies listed in Table 1 were listed in the IRAS Faint Source Catalog, and only 7 of these are ULIRGs. Most (87%) of the galaxies were not detected by IRAS in 3 or more bands. The red WISE colors of the majority of the galaxies in our sample therefore cannot be attributed to extreme infrared luminosities, due either to an intense obscured starburst or an extremely luminous AGN in a ULIRG host.

In addition to ULIRGs, there have been a handful of low-metallicity blue compact dwarfs (BCDs) with extreme (W1 − W2 > 2) mid-infrared colors, raising the possibility that there is a similar origin in the hot dust in the bulgeless galaxy sample. Since the hardness of the stellar radiation increases with decreasing metallicity (e.g., Campbell et al. 1986), and BCDs contain significant star formation, the dust in BCDs can potentially be heated to higher temperatures than is typically seen in starburst galaxies. Given that many of the galaxies in our sample are low-mass galaxies, we explored the possibility that the red colors in our sample have an origin similar to the handful of BCDs described above. Of the 13,862 galaxies in the bulgeless sample, 10,324 (74%) had metallicities available from the MPA/JHU catalog. Of the 353 bulgeless galaxies that meet the W1 − W2 > 0.5 color cut, 54 were listed in the IRAS Faint Source Catalog, and only 7 of these are ULIRGs. Most (87%) of the galaxies were not detected by IRAS in 3 or more bands. The red WISE colors of the majority of the galaxies in our sample therefore cannot be attributed to extreme infrared luminosities, due either to an intense obscured starburst or an extremely luminous AGN in a ULIRG host.
metallicities of the red sources and those of the galaxies with $W_1 - W_2 < 0.5$ in the sample.

Furthermore, if the red WISE colors in our sample are purely a metallicity effect, one would expect a correlation between the mid-infrared color and metallicity, with redder colors corresponding to lower metallicity galaxies. However, we find no correlation between the $W_1 - W_2$ color and metallicity in our sample, which strongly suggests that metallicity effects are not responsible for the red colors, at least for the vast majority of galaxies in our sample.

It is also worth mentioning that while star formation is often cited as the origin of the hot dust emission in BCDs, it is not clear whether in all cases it is simply a by-product of the relatively hard radiation field produced by extreme star
formation in low-metallicity environments, or if AGNs could play a role. Indeed, in some BCDs, high ionization emission lines generally associated with AGNs have been seen (e.g., Izotov et al. 2001, 2004, 2012; Frick et al. 2001), including lines generally associated with AGNs. This detection of these high ionization lines implies the presence of a hard radiation field that cannot be produced by models of high-mass X-ray binaries or massive stellar populations even at low metallicities, but instead requires an AGN and/or fast radiative shocks (Izotov et al. 2012). Izotov & Thuan (2008) also found four low-metallicity dwarf galaxies with very broad Hα emission requiring the presence of an accretion disk around an intermediate-mass black hole. The presence of an AGN in at least some of the BCDs with red WISE colors has not been ruled out.

6. GROWING EVIDENCE OF SMBHS IN BULGELESS AND LOW-MASS GALAXIES

The preliminary analysis above suggests that the red WISE colors discovered in the bulgeless galaxies presented in this work cannot easily be explained by any non-accretion based mechanism for the majority of galaxies. Confirmation of AGN activity requires follow-up high spatial resolution X-ray or infrared spectroscopic observations. We searched both the XMM Newton and Chandra archives for observations of the W1 − W2 ≥ 0.5 galaxies in our sample. Of the 353 galaxies, we found observations of only 3 galaxies in the Chandra archive. Of these observations, two were relatively short at 8.5 ks and 2.0 ks, and unsurprisingly there were no nuclear X-ray detections. The 3σ upper limits for the X-ray luminosity of these sources are large ($L_{0.3-8\text{keV}} < 4 \times 10^{42}$ erg s$^{-1}$ and $L_{0.3-8\text{keV}} < 2 \times 10^{42}$ erg s$^{-1}$, respectively) and therefore do not rule out the possibility that these galaxies contain AGNs. The third source, IRAS F12112+0305, observed for 10 ks, shows a compact, double X-ray nucleus, which is associated with a galaxy that is clearly in the stages of a late merger. The physical separation of these X-ray peaks is 3.7 kpc, and the combined hard X-ray luminosity is $L_{2-10\text{keV}} = 3.8 \times 10^{41}$ erg s$^{-1}$ (Teng et al. 2005). The infrared colors of this source is W1 − W2 = 0.82 and, perhaps not coincidently, this source is classified as a ULIRG. It falls just outside of the Jarrett et al. (2011) “AGN” region in infrared color space due to its red W2 − W3 color. While this source is not typical of our sample, it is the one galaxy in our sample with high-quality X-ray observations, and the X-ray observations confirm the AGN. Unfortunately, none of the low-mass sources in our sample have archival X-ray observations, since they are not generally the targets of X-ray proposals.

We recently acquired XMM-Newton observations of three nearby bulgeless galaxies with red colors. Two of the three galaxies show nuclear X-ray point sources consistent with AGNs. Remarkably, the most X-ray luminous of these two galaxies is a bulgeless irregular optically quiescent dwarf galaxy similar in morphology to He 2–10, but a factor of 10 less massive and a factor of 10 more luminous in the X-rays, making it the lowest mass dwarf with an AGN currently known (N. J. Secrest 2014, in preparation). These preliminary results strongly suggest that WISE is uncovering a population of obscured AGNs that dominate over their host galaxies in the low-mass regime. Finally, we also conducted a preliminary search of the Very Large Array archive for extreme WISE galaxies selected such that W1 − W2 ≥ 0.8. We found one pair of merging galaxies with archival 1.4 GHz radio data (J012217+010027). The radio data show two compact sources coincident with the apparent r-band peaks of the two galaxies, suggesting the presence of AGNs, combined with extended radio emission coincident with material bridging the gap between the galaxies (Hodge et al. 2011).

This work adds to the growing evidence that SMBHs are found in bulgeless and low-mass galaxies. There is incontrovertible X-ray and radio evidence for an AGN in the dwarf galaxy He 2–10 (Reines et al. 2011), and over a hundred dwarf galaxies have recently been discovered with optical spectroscopic signatures of AGNs (Reines et al. 2013). Simmons et al. (2013) have identified a population of optically identified AGNs in bulgeless galaxies. Schramm et al. (2013) recently reported the discovery of three AGNs in low-mass galaxies in the Chandra Deep Field South. One of the three galaxies was detected by WISE and has a

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**Figure 3.** BPT diagram of the bulgeless galaxies from SDSS. Galaxies with mid-IR color consistent with various mid-IR color cuts (from Jarrett et al. 2011, W1 − W2 > 0.8, W1 − W2 > 0.5) are highlighted. The black lines correspond to the demarcations separating star-forming galaxies from the AGNs from Stasinska et al. (2006) and Kewley et al. (2001).

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

**Figure 4.** Mean oxygen abundance 12+log(O/H) of the WISE AGN candidates using the various color cuts explored in this work compared with the galaxies in the bulgeless sample with W1 − W2 < 0.5.

(A color version of this figure is available in the online journal.)
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The discovery of AGN activity in bulgeless and low-mass galaxies is therefore not unprecedented. Furthermore, there are 57 optically identified AGNs in our bulgeless sample, 16 of which also have W1 − W2 greater than 0.5, suggesting that the AGN dominates over the host galaxy emission in these 16 galaxies. In AGN-dominated galaxies, the W2 luminosity is expected to originate almost entirely from the AGN (Stern et al. 2012). In the 16 optical AGNs that also have red WISE colors, the W2 luminosities range from log($L_{W2}$ (erg s$^{-1}$)) = 42.3 to 44.6, with a mean of 43.7. By comparison, the W2 luminosities of our full sample of 337 optically normal galaxies with W1 − W2 > 0.5 range from log($L_{W2}$ (erg s$^{-1}$)) = 41.6 to 45.0, with a mean of 43.8 (erg s$^{-1}$). Thus, even if a putative AGN in these galaxies dominates over its host, the implied total AGN luminosity is by no means extreme.

Based on all available data and the published work on WISE colors of galaxies thus far, the red mid-infrared colors of the bulgeless galaxies presented in this work are difficult to explain without invoking the presence of obscured AGNs. Follow-up multi-wavelength investigations of the full W1 − W2 > 0.5 should be conducted. If these galaxies are discovered not to host obscured AGNs, we emphasize that they are extremely unusual, and that the origin of the host dust needs to be understood in this population.

7. COMPARISON OF WISE AND OPTICAL AGN SELECTION

If the red mid-infrared colors of the galaxies in our sample are indeed due to AGN activity, our investigation has revealed a completely unexpected population in optically quiescent bulgeless galaxies. It is well known that the AGN fraction, based on optical studies, is highest in massive bulge-dominated galaxies (Kauffmann et al. 2003), and drops dramatically in the low-mass regime. While the fraction of bulgeless galaxies that host mid-infrared selected AGNs is still low, if a significant fraction of the galaxies with W1 − W2 > 0.5 are confirmed to host AGNs, the AGN detection rate based on WISE could be a factor of up to ≈6 larger than the optical AGN detection rate, at least in galaxies that are not massive and bulge-dominated. In order to compare the general dependence of WISE AGN selection with optical AGN selection as a function of stellar mass, we obtained the WISE colors for all galaxies in the Simard et al. (2011) catalog for all host morphologies. Again we cross-matched the Simard et al. (2011) catalog with the WISE all-sky data release catalog to within <1", requiring a detection threshold above 5σ in the W1, W2, and W3 bands. In Figure 5, we show the fraction of galaxies classified as AGN by WISE according to the various color cuts as a function of stellar mass. Although the reliability of AGN selection is a function of the adopted color cut, Figure 5 clearly shows that the AGN fraction, based on infrared color selection, is highest at the lowest stellar masses and drops dramatically at higher stellar masses. This result is in direct contrast with results from optical spectroscopic surveys. In the Kauffmann et al. (2003) study of 22,623 narrow-line AGNs drawn from SDSS, the AGN fraction approaches nearly 100% for all emission line galaxies at the highest masses and drops dramatically with decreasing stellar mass (see Figure 5, solid histogram in top panel, in Kauffmann et al. 2003). A key and striking result from this study is that WISE reveals a population of optically hidden AGNs in the lowest mass galaxies, and that the incidence of WISE AGNs remarkably follows an opposite trend with mass than that which is found in optical spectroscopic studies. We also note that, as discussed above, WISE detects AGNs in galaxies where the AGN dominates over the host galaxy emission. Indeed, as can be seen from Figure 5, none of the WISE color cuts select the bulk of the optically identified AGNs at higher masses, since the AGNs do not dominate over the host galaxy emission. Mid-infrared color selection is therefore selecting a more extreme population of AGNs that is more prevalent in the low-mass regime.

8. SUMMARY

We have conducted an investigation of the WISE colors of 13,862 low-redshift galaxies drawn from and classified as bulgeless from the SDSS catalog of bulge/disk decompositions from Simard et al. (2011). Our main results can be summarized as follows:

1. We have identified a population of bulgeless galaxies that display extremely red mid-infrared color indicative of hot dust, which is highly suggestive of a dominant AGN. Depending on the WISE color selection employed, the number of AGN candidates ranges from 25 to over 300.

2. The vast majority of these galaxies display no optical AGN signatures in their SDSS spectra, and many appear to be “pristine” isolated galaxies with no signs of interactions.

3. Based on existing data, we have explored other known scenarios that can heat the dust to high temperatures including extreme star formation and star formation in low-metallicity environments, but none of these scenarios appear to explain the observed colors of this sample.

4. If these galaxies do host AGNs, the AGN detection rate can be up to a factor of ≈6 larger than the optical AGN detection rate in this host galaxy demographic.

5. We compare the AGN detection rate based on infrared color selection with the optical AGN detection and find that the fraction of all galaxies identified as candidate AGNs by WISE is highest at the lowest stellar masses and drops dramatically in the highest mass galaxies, in striking contrast to the findings from optical studies.

The discovery of optically quiescent bulgeless with AGNs will add to the growing evidence that SMBH growth takes place...
through secular processes and can potentially help discriminate between scenarios for the seed population from which they arose. Follow-up multi-wavelength high spatial-resolution observations of this sample are critical to confirm the presence of AGNs in these galaxies, to obtain more precise estimates of the bulge masses, and to constrain the black hole masses, accretion rates, and nuclear bolometric luminosities. If, on the other hand, these galaxies do not turn out to host AGNs, they are very unusual and the origin of their hot dust is of interest in itself. This scenario would also have an impact on the use and reliability of Wise color selection of AGNs in other surveys.

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