THE MID-INFRARED EMISSION OF NARROW-LINE ACTIVE GALACTIC NUCLEI: STAR FORMATION, NUCLEAR ACTIVITY, AND TWO POPULATIONS REVEALED BY WISE

DAVID J. ROSARIO, LEONARD BURTSCHER, RICHARD DAVIES, REINHARD GENZEL, DIETER LUTZ, AND LINDA J. TACCONI
Max Planck Institute for Extraterrestrial Physics, Postfach 1312, 85741 Garching, Germany
Received 2013 July 2; accepted 2013 September 12; published 2013 November 8

ABSTRACT

We explore the nature of the long-wavelength mid-infrared (MIR) emission of a sample of 13,000 local Type II (narrow-line) active galactic nuclei (AGNs) from the Sloan Digital Sky Survey (SDSS) using 12 μm and 22 μm photometry from the WISE all-sky survey. In combination with FIRST 1.4 GHz photometry, we show that AGNs divide into two relatively distinct populations or “branches” in the plane of MIR and radio luminosity. Seyfert galaxies lie almost exclusively on an MIR-bright branch (Branch A), while low-ionization nuclear emission line galaxies (LINERs) are split evenly into Branch A and the MIR-faint Branch B. We devise various tests to constrain the processes that define the branches, including a comparison to the properties of pure star-forming inactive galaxies on the MIR-radio plane. We demonstrate that the total MIR emission of objects on Branch A, including most Seyfert galaxies, is governed primarily by host star formation, with ≈15% of the 22 μm luminosity coming from AGN-heated dust. This implies that ongoing dusty star formation is a general property of Seyfert host galaxies. We show that the 12 μm broadband luminosity of AGNs on Branch A is suppressed with respect to star-forming galaxies, possibly due to the destruction of PAHs or deeper 10 μm Si absorption in AGNs. We uncover a correlation between the MIR luminosity and [O iii] λ5007 luminosity in AGNs. This suggests a relationship between the star formation rate and nuclear luminosity in the AGN population, but we caution on the importance of selection effects inherent to such AGN-dominated emission-line galaxies in driving such a correlation. We highlight the MIR-radio plane as a useful tool in comparative studies of star formation and nuclear activity in AGNs.

Key words: galaxies: active – galaxies: photometry – galaxies: Seyfert – galaxies: star formation – galaxies: statistics – infrared: galaxies – radio continuum: galaxies – surveys

Online-only material: color figures

1. INTRODUCTION

Through their enormous and concentrated energetic output, supermassive black holes (SMBHs) are expected to play an important role in the evolution of their host galaxies. As yet elusive is a detailed understanding of the interplay between accretion onto the black hole and their final output. Recently, patterns exhibited by stellar mass black holes have been shown to extend to their supermassive cousins, allowing various relationships to be proposed between the accretion rate, radiative efficiency, and mechanical output via relativistic outflows (e.g., Maccarone et al. 2003; Merloni et al. 2003; Chu-ray et al. 2005; Trump et al. 2011). At low specific accretion rates (Eddington ratios λE ≲ 10−2), the flow onto the SMBH is believed to be radiatively inefficient, possibly advecting much of its thermal energy through the event horizon. A substantial fraction of the accreted mass is channeled into radio-emitting jets, likely mediated by the magnetic field of the SMBH. At higher λE, the accretion flow settles into a radiatively efficient thin disk, which produces a powerful X-ray and extreme-ultraviolet (EUV) radiation field at the expense of the relativistic outflow. The bright high-energy spectrum of such an active galactic nucleus (AGN) can strongly ionize gas out to kiloparsecs, resulting in extended AGN emission line regions.

In most AGNs, the direct EUV is inaccessible due to its high optical depth to gas and dust from the vicinity of the SMBH and on galaxy scales. Much of the absorbed EUV is reprocessed to the mid-infrared (MIR) from AGN-heated dust, at hundreds of K, located in the putative parsec-scale “torus.” Indeed, AGN spectral energy distributions (SEDs) show clear evidence for excess hot dust in the MIR (e.g., Sanders et al. 1989; Netzer et al. 2007; Wu et al. 2009; Shao et al. 2013). Therefore, the relative output of an AGN between the MIR and radio wavelengths may serve as a tracer of the accretion mode of the growing SMBH.

There is, however, an important complication to this simple argument. The emission of galaxies in the MIR is also influenced by other processes, most importantly the heating of very small dust grains by star formation (SF) and evolved stellar populations (e.g., Rowan-Robinson & Crawford 1989; Desert et al. 1990; Draine & Li 2001; Groves et al. 2012), as well as the excitation of the complex of bands from polycyclic aromatic hydrocarbons (PAHs; Draine & Li e.g., 2007). Prior to an investigation of the accretion properties of AGNs, an account must be made for the MIR emission from these other processes. Such an approach also affords a worthwhile by-product. The thermal infrared is a valuable tracer of SF and is relatively free of the effects of extinction or optical depth saturation that affects the UV or optical emission lines (e.g., Calzetti et al. 2007). In massive, metal-rich galaxies, such as AGN hosts, most of the emission from young stars is reprocessed by dust in molecular clouds and emitted in the IR. Therefore, a detailed study of the MIR in AGNs can provide a handle on both the accretion properties of the nuclear source and its relationship to SF in the host galaxy.

Theoretical and empirical arguments support a connection between SF and nuclear activity in AGN hosts, either by direct synchronization between a starburst and the fueling of the nucleus (Sanders et al. 1988; Norman & Scoville 1988; Storchi-Bergmann et al. 2001; Davies et al. 2007), or indirectly mediated by the availability of cold gas needed for luminous AGN activity (Heller & Shlosman 1994; Rosario et al. 2013). In the era of the
Infrared Space Observatory (ISO) and the Spitzer Space Telescope, much work has examined the interplay between AGNs and SF through the use of MIR spectroscopy (Genzel & Cesarsky 2000; Verma et al. 2005; Soifer et al. 2008), employing fine-structure emission lines of various ionized species (e.g., Genzel et al. 1998; Sturm et al. 2002; Meléndez et al. 2008; Tommasin et al. 2010; Diamond-Stanic & Rieke 2012), PAH features and their relative strengths (e.g., Schweitzer et al. 2006; Shi et al. 2007; O’Dowd et al. 2009; Diamond-Stanic & Rieke 2010; LaMassa et al. 2012), and continuum luminosities and MIR colors (e.g., Wu et al. 2009; LaMassa et al. 2010). These studies have greatly enhanced our understanding of the MIR phenomenology and physics relevant to the AGN–SF connection, firming up such results as the increased abundance of AGN signatures in IR-luminous galaxies (e.g., Genzel et al. 1998; Nardini et al. 2008), the anticorrelation of PAH strength with AGN prominence (e.g., Clavel et al. 2000; O’Dowd et al. 2009; LaMassa et al. 2010), and the greater depth of the 10 μm Si absorption feature in Type II AGNs (e.g., Shi et al. 2006; Hao et al. 2007). However, as discussed in Section 2.2.2, most of these studies were limited to either very nearby or fairly luminous systems, selected based on the capabilities of the early Infrared Astronomical Satellite (IRAS; Soifer et al. 1987; Rush et al. 1993).

A recent huge leap forward comes from the surveys from the Wide-field Infrared Survey Explorer (WISE), with more than two orders of magnitude deeper MIR sensitivity than IRAS over the whole sky, enabling a greater dynamic range and better photometry of sources over a wider range of redshifts. In this paper, we use MIR and radio photometry from the WISE and Faint Images of the Radio Sky at Twenty-cm (FIRST) surveys to assess the dominant source of the total, galaxy-integrated MIR emission in local (z < 0.15) narrow emission line selected AGNs from the Sloan Digital Sky Survey (SDSS). The data and sample properties are laid out in Section 2. In Section 3, we discuss the diagnostics of the MIR–radio luminosity plane and outline two distinct populations of AGNs, which we discuss in the context of AGN ionization classes. We perform various tests using ancillary measurements from the SDSS and AKARI surveys (Section 4) and then synthesize our findings toward an understanding of the nature of the two populations (Section 5).

Throughout this work, we assume a Λ cold dark matter concordance cosmology with H₀ = 73 km s⁻¹ Mpc⁻¹ and ΩΛ = 0.7.

2. SAMPLE SELECTION AND DATA

2.1. SDSS Emission-line AGNs

Emission line selected AGNs were drawn from the MPA-JHU database of spectral measurements, based on the SDSS Data Release 7 (DR7; Abazajian et al. 2009). This database is restricted to objects with galaxy-like spectra and narrow Balmer lines, specifically excluding broad-line (Type I) AGNs. Therefore, our sample consists almost exclusively of narrow-line (Type II) AGNs. From the entire catalog of 818,333 unique galaxies, we chose all objects satisfying the following criteria:

1. a high-quality spectroscopic redshift in the range 0.02 < z < 0.15;
2. signal-to-noise ratio (S/N) > 3 in the emission lines of [O III] λ5007, Hβ, Hα, and [N II] λ6584, as well as an S/N > 2 in the weaker [S II] λ6720 line doublet;
3. a location in the standard “Baldwin–Phillips–Terlevich (BPT)” diagram of [O III] λ5007/Hβ versus [N II] λ6584/Hα (Baldwin et al. 1981; Veilleux & Osterbrock 1987) above the curve that separates objects with AGN-dominated ionization from composite and SF galaxies (Kewley et al. 2001, 2006). These are objects in the Seyfert and LINER domains of the BPT diagram;
4. equivalent width (EW) of Hα > 3 Å to ensure that weak LINERs are excluded from the sample. Lines in systems with weaker Hα can arise primarily in shocks or through the UV field from evolved stars, rather than by a nuclear source (Cid Fernandes et al. 2011).

From this subset of 13,339 AGNs, we separated high-ionization AGNs (Seyferts) from LINERs using the [S II] λ6720/Hα criterion of Kewley et al. (2006), Equations (7) and (12). The use of a simple cut in [O III] λ5007/Hβ ratio of 3.0 to separate high- and low-ionization AGNs leads to considerable mixing at the boundaries of these populations in the standard BPT diagram. Hence, we adopted the use of the fainter [S II] line as an additional selection criterion, even though it tends to reject intrinsically lower luminosity AGNs with faint emission line fluxes.

We also make use of host stellar mass (M∗) and 4000 Å break (D_n4000) measurements from the MPA-JHU database. The masses were derived from fits to the five-band SDSS photometry of the hosts, following the methodology of Salim et al. (2007). The procedure for D_n4000 measurements is described in Kauffmann et al. (2003b).

2.1.1. Selection Effects Inherent to SDSS Emission Line Selected AGNs

AGNs selected through BPT-based criteria from the SDSS spectroscopic database give us by far the largest census of local nuclear activity. While a remarkable resource for AGN studies, a finer understanding of the relationship between AGN activity and the properties of host galaxies requires an appreciation of the biases inherent to the selection of such AGN samples.

Standard BPT criteria divide emission-line galaxies into three populations: AGN-dominated, SF-dominated, and so-called “composite” systems. The last category includes objects that show line ratios intermediate to SF- and AGN-dominated systems and contain a large number of AGNs with substantial SF in their inner regions (e.g., Kauffmann et al. 2003a; Juneau et al. 2011). AGN-dominated systems, those that lie above the curve from Kewley et al. (2001), have their line emission from within the SDSS aperture largely arising in AGN ionized gas. While cleanly separating out AGNs, this criterion additionally selects against objects with strong SF in the central aperture. AGN-dominated systems will have, on average, a lower SFR within the SDSS aperture than purely SF or composite systems.

The SDSS aperture (3′′ is diameter) covers between 0.6 and 3.8 kpc (projected) in galactic radius across our working redshift range of 0.02–0.15. This may be compared to the typical effective radii of massive galaxies, which range from 2 to 8 kpc (Trujillo et al. 2006). In general, the SDSS aperture covers less than half of a galaxy’s light. The typical size of the narrow-line region (NLR), in which most of the AGN-ionized emission originates, is ∼1 kpc for bright Seyfert galaxies (Bennert et al. 2006). Therefore, almost all of the emission from the AGN will be sampled by the SDSS aperture. As the physical radius subtended by the SDSS aperture increases with redshift, a growing fraction of an average galaxy is sampled by the SDSS spectrum. While at low redshifts AGN-dominated systems may still have considerable SF outside the region probed by the SDSS aperture, at higher redshifts, as more of the galaxy falls within the aperture, AGN-dominated systems.
become increasingly special objects, containing either fairly luminous AGNs, galaxies with weak SF, or objects where most of the SF either is obscured or lies on the outskirts of the galaxy.

Consider an AGN host galaxy with a certain nuclear luminosity $L_{\text{AGN}}$ and total SFR. In general, this SFR is spread over the host galaxy, with a fraction $f_{\text{in}}$ that lies within the SDSS fiber aperture. The emission-line contribution purely from H\textsc{ii} regions in the SDSS spectrum is broadly set by SFR and $f_{\text{in}}$ (we marginalize over other factors such as host metallicity and morphology for this heuristic argument). If $L_{\text{AGN}} > L_{\text{AGN},c}$, a certain critical value, the emission-line spectrum of the AGN-ionized gas will be brighter than that from H\textsc{ii} regions and the galaxy will enter the AGN-dominated region of the BPT diagram and satisfy our selection. $L_{\text{AGN},c}$ is proportional to the SFR and $f_{\text{in}}$—as $f_{\text{in}} \times \text{SFR}$ increases, $L_{\text{AGN},c}$ also increases. Therefore, among strongly SF galaxies or galaxies at higher redshifts (where the SDSS fiber covers a larger part of the host galaxy), AGNs have to be more luminous to enter the AGN-dominated part of the BPT diagram, leaving a larger fraction of the active population in the composite region of the diagram. This effect will also force a correlation between $L_{\text{AGN}}$ and SFR among line-selected AGNs, even if one is not physically present.

### 2.2. WISE All-sky Survey

**WISE** (Wright et al. 2010) has mapped the entire sky in four MIR bands at 3.4 μm, 4.6 μm, 12 μm, and 22 μm. A public catalog is available consisting of photometry from the all-sky survey atlas of point-like and extended sources detected with an S/N > 5 in at least one of the four WISE bands. The catalog is not uniform, since the depth of the WISE imaging varies considerably across the sky. The astrometry accuracy of the catalog, tied to the Two Micron All Sky Survey (2MASS) coordinate system, is better than 200 mas.

We cross-matched the SDSS-selected AGNs with the WISE all-sky survey catalog available from the IPAC/IRSA service, using a simple cone search with a tolerance of 2″. More than 98% had a counterpart in the WISE survey, almost 75% of which also had S/N > 2 detections in both 12 and 22 μm bands.

We rely on the photometry performed by the WISE all-sky survey pipeline, details of which may be found in the Data Release Supplement. The pipeline provides several different photometric measurements for sources in all four WISE bands. The primary photometry is performed by point-spread function (PSF) decomposition, assuming that pipeline targets are composed of blends of one to two point sources (the “profile-fitting” or PRO photometry). A maximum-likelihood model of the source plane is simultaneously fit in all four bands for contiguous batches of sources. In addition, various flavors of circular and elliptical aperture photometry are also provided by the survey pipeline.

In this work, we only employ photometry in the two longer wavelength bands. The FWHM of the WISE PSFs is ≈6′′8 in the 12 μm (W3) band and ≈11′′8 in the 22 μm (W4) band. At the lowest redshifts, galaxies could be extended in the WISE images, even beyond the large 22 μm PSF. The profile-fit $\chi^2$ in a band serves as a way to identify if the image of a source in that band is likely to be extended. The WISE pipeline uses a value of reduced $\chi^2 > 3$ to flag a source as extended. We find that, of the roughly 12,440 sources in our “working sample” (those with better than 2σ detections in either W3 or W4), only 264 have a reduced $\chi^2 > 3$ in either the W3 or W4 bands: 80% of these lie at $z < 0.05$, and 95% are associated with an extended counterpart in the 2MASS all-sky near-IR survey. The vast majority of the sources in our sample are unresolved in the W3 and W4 bands of WISE, and for these we adopt the PRO magnitudes as the best estimates of their photometry. For the resolved sources with 2MASS counterparts, the WISE pipeline generates aperture photometry in ellipses matched and scaled to the sizes and shapes of the corresponding 2MASS sources, which we adopt as the best estimates of their magnitudes. The W3 magnitudes of extended sources have been boosted by a small additive factor of 0.44 mag to account for imperfect background subtraction and other effects shown to influence the aperture photometry (see WISE All-Sky Survey Explanatory Supplement Sec VI.3.e). We exclude the remaining 32 extended sources with no 2MASS counterparts from our sample.

#### 2.2.1. MIR Features Probed by the WISE Bands

In Figure 1, we examine the parts of the IR SEDs sampled by the two WISE bands in both SF and pure AGN torus-dominated cases. Two representative SF galaxy templates from the Chary & Elbaz (2001) library are plotted, corresponding to total IR (8–1000 μm) luminosities of $10^{10} L_\odot$ (a moderately SF galaxy) and $10^{12} L_\odot$ (a local ultraluminous IR galaxy (ULIRG)). For a torus-dominated SED, we show the template of Mor & Netzer (2012), an average from MIR observations of local Type I AGNs spanning a wide range in luminosity.

At all redshifts in this study, the W3 band covers the complex of emission bands at 8–13 μm produced by PAHs, as well as the broad silicate absorption feature at 10 μm. The W4 band, on the other hand, is free of PAHs and serves as a good measure of the pure dust continuum emission, which, in star-forming galaxies, comes from warm dust in the high-temperature tail of the typical distribution of grains. Due to the systematic variation of PAH EWs with total IR luminosity (Chary & Elbaz 2001; Dale et al. 2001), the W3–W4 colors of SF galaxies are bluer in low-luminosity IR galaxies (i.e., those with low levels of SF) than in IR-luminous systems, such as ULIRGs.

Compared to SF templates, pure AGN templates are flat and fairly featureless in the 10–30 μm wavelength band (Netzer et al. 2007; Mullaney et al. 2011; Mor & Netzer 2012). Theoretical
studies of AGN-heated dust “tori” suggest a broad range of peak wavelengths around 15–30 μm depending on the structure of the dust and the intrinsic AGN spectrum (Hönig et al. 2006; Fritz et al. 2006; Nenkova et al. 2008). Real AGNs, however, frequently show PAH features in their spectra, from SF in their host galaxies. Significant silicate absorption is also found in their SEDs, especially among Type IIs (e.g., Deo et al. 2007; Goulding et al. 2012). The W3–W4 color of a typical AGN lies within the range shown by SF galaxies—a simple color criterion involving these bands cannot easily distinguish between SF- and AGN-dominated systems.

2.2.2. Comparison to the IRAS Extended 12 μm AGN Sample

In Figure 2, we observed-frame 12 μm luminosities against redshift of SDSS AGNs with WISE W3 band photometry (small black points) along with a subset of AGNs from the IRAS-based extended 12 μm sample of galaxies (large red points). The latter come from the compilation of Wu et al. (2009) and constitute a large fraction of local Seyferts that have been studied spectroscopically with the Spitzer/IRS instrument (Buchanan et al. 2006; Wu et al. 2009; Tommasin et al. 2010; LaMassa et al. 2010). The selection of the extended 12 μm sample of AGNs was set by the depths of the IRAS Faint Source catalog v2 (Rush et al. 1993), and all have 12 μm fluxes \( f_{12,\text{IRAS}} \geq 0.22 \text{ Jy} \). In comparison, the WISE all-sky survey reaches down to 0.5 mJy (2σ) at 12 μm. Therefore, the sources typically studied using detailed IRS spectroscopy are either much nearer or much more luminous than the vast majority of the sources in our sample. From Figure 2, we see that the typical redshift of AGNs from the 12 μm sample is z ~ 0.02, whereas most of our AGNs lie at z ~ 0.1. Since the scales covered by nominal IRS apertures (\( \approx 15'' \)) are similar to those covered by the WISE PSF, most earlier spectroscopic studies probed AGN hosts on radii of \( \lesssim \) few kpc—just the circum-nuclear regions—while most of our AGNs are photometered over the entire galaxy. In addition, our objects cover a much larger swathe of MIR luminosity than existing samples over the redshifts where the two samples overlap, and they are not restricted to the IR-luminous systems detected by IRAS. These differences should be borne in mind when comparing our findings to results in the contemporary literature.

2.3. FIRST 20 cm Radio Survey

For a radio survey complementary in many ways to the SDSS, we turn to the Very Large Array (VLA) FIRST 20 cm (1.4 GHz) survey (Becker et al. 1995). The current public catalog combines observations of about 10,000 deg^2 of sky coincident with the SDSS. The resolution of the FIRST survey is \( \approx 5'' \), with an astrometric accuracy of 50 mas. The integrated flux of FIRST sources is measured using two-dimensional Gaussian fits to the source profile on the survey maps. For a small fraction of sources that are very extended and jetted, those corresponding to classical radio galaxies, a Gaussian profile fit is an inadequate representation of the source structure, and the FIRST photometry of such sources may be in error. Since the vast majority of the sources in our sample are at low power (\( L_{1.4} \lesssim 10^{23} \text{ W Hz}^{-1} \)), the source sizes are likely to be close to or below the resolution of the survey, and the fluxes will be accurate.

We cross-matched the SDSS-selected AGNs with the FIRST source catalog using a search tolerance of 2″. This yielded FIRST counterparts for 23% of LINERs and 19% of Seyferts, about two times higher than the SDSS counterpart fraction of FIRST sources at the \( r < 18 \) magnitude limit of the SDSS spectroscopic survey (de Vries et al. 2007). The difference is due to our stringent emission-line selection, which picks out more luminous systems. Relaxing the Hα EW requirement, for example, yields radio detection rates of \( \approx 10% \). Due to the relative shallowness of FIRST, only a subdominant fraction of the AGN population can be probed completely by this study. In the rest of this work, unless otherwise stated, we use the term AGNs, LINERs, or Seyferts to refer to the subpopulations detected in both WISE and FIRST surveys.

2.4. AKARI All-sky Survey

The far-infrared (FIR) is dominated by radiation from cold dust with temperatures \(<100 \text{ K} \). In galaxies, this component of the dust emission spectrum is produced almost exclusively in star-forming regions or from diffuse cirrus. In FIR-luminous galaxies, the component from SF is paramount, and, even in fairly luminous AGNs, the FIR luminosity can be taken as a relatively clean measure of the SFR (e.g., Netzer et al. 2007; Rosario et al. 2012).

In Section 3, we investigate the relationship between SF and the MIR luminosity of AGNs. For a sample of bona fide star-forming AGNs to aid in this study, we identify a subset of FIR-bright AGNs from the AKARI/FIS all-sky survey Bright Source Catalog. We cross-match our AGNs with the catalog using a search tolerance of 15″. The large tolerance is warranted by the greater positional uncertainty of the FIR catalog due to the broad AKARI PSF at 90 μm (\( \approx 50'' \) FWHM). A total of 703 sources were identified with reliable 90 μm photometry (FQUAL90 = 3). The 0.55 Jy detection limit of the AKARI/FIS catalog corresponds to a 90 μm luminosity limit of \( \approx 10^{9} L_{\odot} \) at \( z = 0.02 \) and \( \approx 10^{10.9} L_{\odot} \) at \( z = 0.15 \), picking out moderately luminous star-forming galaxies at all redshifts.
3. TWO POPULATIONS OF AGNs: THE MIR–RADIO PLANE

In this section, we demonstrate that AGNs divide into two relatively distinct populations in the plane of MIR and radio luminosity. Seyferts and LINERs distinguish themselves by differentiating into these two populations in different proportions. We examine the effects of survey limits and whether this dichotomy is preserved even among radio-undetected AGNs.

The rest-frame monochromatic MIR luminosities at 12 and 22 μm used here are derived from the WISE W3 and W4 magnitudes, applying a k correction based on a Chary & Elbaz (2001) template of a star-forming galaxy with a total IR luminosity of $10^{11} L_\odot$. The k correction is small, amounting to 0.03 mag at 12 μm and 0.4 mag at 22 μm for galaxies at $z = 0.15$. The full range of IR templates from Chary & Elbaz (2001) gives a maximum variation in the k correction of ±0.2 mag. A flat radio spectrum per unit energy was assumed, requiring no additional k correction to get rest-frame 1.4 GHz luminosities. Since the radio output of a sizable fraction of AGNs is governed by SF (Section 5.2.3), true spectral indices may vary as high as 0.5. However, the choice of spectral index makes no significant difference to our results.

In the left panel of Figure 3, we plot the rest-frame 12 μm monochromatic luminosity ($L_{12}$) against the rest-frame 1.4 GHz luminosity ($L_{1.4}$) of SDSS/WISE-FIRST AGNs. They divide quite clearly into two fairly distinct populations in the $L_{12}$–$L_{1.4}$ plane. We use the term “branches” to describe the two populations and will refer to them as such in the rest of the paper. Objects on Branch A have a high $L_{12}$/$L_{1.4}$ ratio and delineate a steep trend between 12 μm luminosity and radio luminosity. On Branch B, sources show a lower $L_{12}$/$L_{1.4}$ ratio and a shallow dependence between $L_{12}$ and $L_{1.4}$. The dashed line in the figure roughly separates the two branches and serves as a guide to the eye.

The two branches persist in the plot of $L_{22}$ versus $L_{1.4}$ (right panel of Figure 3), but the lower branch is less populated. This is because of the shallower depth of the WISE survey in the W4 band: IR-faint objects are not significantly detected in W4, which preferentially affects the density of objects in Branch B. Nevertheless, this diagram shares many features in common with the left panel, implying a close continuity between the emission of AGNs in both MIR bands. Indeed, if one divides sources into two branches based on their position in the left panel, they remain in two branches in the right panel as well (as shown with different colored points).

In Figure 4, we show the $L_{12}$–$L_{1.4}$ plane separately for LINERs and Seyferts. Remarkably, despite being divided purely based on optical emission line criteria, the two AGN classes show strikingly different behavior in this diagram. Seyferts cluster tightly and typically lie at $L_{12} > 10^{43}$ erg s$^{-1}$, almost exclusively along Branch A ($\approx 6\%$ of Seyferts lie on Branch B). On the other hand, LINERs divide roughly equally between both branches. LINERs on Branch A are slightly less luminous in $L_{12}$ than Seyferts of the same $L_{1.4}$, tending to lie closer to the dividing line.

The division of AGNs into two branches based on MIR and radio properties is preserved across all redshifts in our sample (left panel of Figure 5), though the most luminous sources, in both the MIR and the radio, are found at the higher redshifts simply because of the larger volumes probed. The characteristic flux limits of the WISE and FIRST surveys correspond to an increasing $L_{12}$ and $L_{1.4}$ luminosity limit with redshift (dashed vertical and horizontal lines). Sources on Branch A are luminous enough in the MIR that they lie well above the luminosity limit at all redshifts. The normalization and slope of Branch A in the $L_{12}$–$L_{1.4}$ plane do not appear to change with redshift, suggesting a physical basis for this branch that remains constant to $z = 0.15$. Sources in Branch B typically lie just around the $L_{12}$ limit—this suggests that the weak slope to this branch is not real, but is driven mostly by Malmquist bias.

As discussed before, the relative shallowness of the FIRST survey ultimately limits the fraction of AGNs that can be classified into branches, ranging from 40% at $z = 0.02$ to 15% at $z = 0.1$. In contrast, the deep WISE photometry allows us to estimate MIR luminosities for most SDSS AGNs, since more than 90% of the parent sample is detected in the W3 band. Could the $L_{12}$ distribution of sources undetected in FIRST give us an indication as to their likely location on the MIR–radio plane?
Is the coherence of Branch A seen at low redshifts preserved among AGNs at high redshifts that lie below the FIRST flux limits?

To overcome the complexities of redshift-dependent limits, we consider a narrow redshift slice at $0.080 < z < 0.085$, roughly at the middle of the full range of redshifts. In the right panel of Figure 5, we compare the $L_{12}$ distributions of the radio-detected and radio-undetected SDSS/WISE AGNs and attempt to understand their differences. One may view these histograms as a projection of the MIR—radio plane of Figure 3 onto the Y-axis for sources in the small redshift interval. For the 17% of the sources detected in FIRST, we plot distributions of $L_{12}$ split by branch, as shown by the gray histograms. The $L_{12}$ of FIRST-detected sources is bimodal, consistent with the patterns in the MIR—radio plane. Of the remaining sources, those detected in the W3 band but undetected by FIRST compose 77% of the full SDSS sample at these redshifts. These are plotted as the open colored histograms in the figure, with Seyferts shown in blue and LINERs shown in red. Our hypothesis is that a substantial fraction of LINERs should be on an extrapolation of Branch B below the FIRST detection limit. The $L_{12}$ distribution of radio-undetected LINERs (red histogram) is consistent with a substantial fraction on Branch B, in parallel with radio-detected LINERs.

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

Figure 4. Rest-frame 12 μm luminosity ($L_{12}$) versus 1.4 GHz luminosity ($L_{1.4}$) of SDSS emission line selected AGNs in the redshift range $0.02 < z < 0.15$. The dashed line that divides the two branches from Figure 3 is also plotted. LINERs and Seyferts are shown in the left and right panels, respectively. The two classes of AGNs distribute very differently in this diagram. While LINERs occupy both branches, Seyferts are almost completely on Branch A.

Figure 5. Left: rest-frame 12 μm luminosity ($L_{12}$) versus 1.4 GHz luminosity ($L_{1.4}$) of SDSS emission line selected AGNs colored by redshift, according to the color bar at right. The dashed lines show the typical luminosity limit of the WISE and FIRST surveys at a set of illustrative redshifts, also colored according to the same color bar. Sources on Branch A are considerably brighter than the $L_{12}$ limits at their corresponding redshifts, and the correlation on the diagram from objects on this branch is seen consistently at all redshifts. On the other hand, sources on Branch B lie close to the $L_{12}$ limits at all redshifts. The weak correlation seen for Branch B is driven mostly by redshift biases, in that the most luminous sources are seen only at the highest redshifts in our sample. Right: $L_{12}$ distributions of AGNs in the narrow redshift interval $0.080 < z < 0.085$, spanning the range of radio luminosity covered by Branch A over the entire AGN sample. The shaded histograms show sources that are detected in the FIRST survey. Sources on Branch A (light gray histogram) and Branch B (dark gray histogram) show different distributions of $L_{12}$, as expected from their locations on the MIR—radio plane. The colored open histograms show sources that lie below the FIRST detection limit. The $L_{12}$ distribution of radio-undetected Seyferts (blue histogram) is consistent with most of them lying on an extrapolation of Branch A below the FIRST detection limit. The $L_{12}$ distribution of radio-undetected LINERs (red histogram) is consistent with a substantial fraction on Branch B, in parallel with radio-detected LINERs.
$L_{12}$ much higher than the MIR luminosity limit, consistent with them lying on an extension of Branch A below the radio limit.

We can illustrate this more quantitatively in the following manner. Since the ridgeline of Branch A has a non-zero slope in the MIR–radio plane, sources with higher $L_{1.4}$ correspond to higher $L_{12}$, with some scatter given by the width of Branch A. For a representative set of $L_{1.4}$ above, at, and below the FIRST detection limit at $z = 0.08$, we calculate corresponding $L_{12}$ from the Branch A ridgeline (see Figure 6) and plot them as vertical solid and dotted lines. The range of $L_{12}$ spanned by the dotted lines is equivalent to the range spanned by the entirety of Branch A galaxies over our entire redshift range. It encompasses the Branch A histogram at this redshift (by construction), as well as the peak of the Seyferts. The solid line, corresponding to the radio detection limit, delineates a transition between the radio-detected sources of Branch A and the peak of the radio-undetected Seyferts, as one would expect if a substantial fraction of these Seyferts lay on an extension of Branch A.

4. THE NATURE OF THE TWO BRANCHES

Here we investigate the likely cause for the splitting of the AGN into two populations in MIR–radio space. This has important implications for our understanding of the AGN population. If the dichotomy is driven by differences in the level of SF-heated dust, then our results would imply that the vast majority of Seyferts are in SF galaxies, even those with AGN-dominated nuclear emission lines. If, on the other hand, the difference is driven by a higher level of AGN-heated dust in Seyferts, then the MIR–radio diagram may be viewed as a sensitive tracer of reprocessed high-energy radiation from AGNs and will allow us some insight into the intrinsic differences in the nuclear SEDs of these two classes of systems. Our approach is to devise a series of empirical tests that make use of the high-quality ancillary data and measurements available for SDSS galaxies.

4.1. Star-forming Galaxies on the MIR–Radio Plane

A simple empirical diagnostic is the location of pure inactive, star-forming galaxies in MIR–radio space. AGNs are mostly found in fairly massive galaxies ($M_* \gtrsim 10^{10.5} M_\odot$), and since many galaxy properties, including SFR, correlate strongly with stellar mass, a fair comparison of SF properties between AGNs and inactive galaxies requires, minimally, that the comparison take into account stellar mass related biases (Silverman et al. 2009; Xue et al. 2010; Rosario et al. 2013). For this, we construct a control sample of pure star-forming galaxies matched to AGNs in both redshift and $M_*$. We select galaxies that lie below the curve that separates star-forming from composite systems in the BPT diagram (Equation (1) in Kewley et al. 2006). To ensure good discrimination in this diagram, we also require the galaxies to be detected with an S/N $> 3$ in the Hα, Hβ, and [N II] λ6584 emission lines. Only a valid upper limit is needed on [O III] λ5007 to select SF galaxies in this manner. After binning the AGNs and inactive galaxies in $\Delta \log M_* = 0.1$ bins in stellar mass and $\Delta z = 0.01$ bins in redshift, we randomly assign one inactive galaxy to each AGN in a bin. In practice, since there exist very few purely SF galaxies with large stellar masses, some AGNs are left unmatched at the high-mass end ($M_* \gtrsim 10^{11.5} M_\odot$). We account for the unmatched AGNs in the following analysis. The inactive control sample was cross-matched to the WISE all-sky survey catalog and the VLA-FIRST catalog in the same fashion as the AGNs, and the MIR and radio photometry was extracted from these catalogs in a similar way.

In Figure 6, we plot again the MIR–radio diagrams for the AGNs, as in Figure 3, but also include the SF galaxies as red points. The SF galaxies describe a tight relation in MIR–radio space. In the $L_{12}$–$L_{1.4}$ diagram (left panel), the SF galaxies overlap with the upper end of the distribution of AGNs on Branch A, but essentially no inactive SF galaxies are found on Branch B. SF galaxies also lie exclusively on Branch A in the $L_{22}$–$L_{1.4}$ diagram (right panel), but here the SF galaxies generally overlap with the AGNs. In both panels, linear regression lines for AGNs and inactive galaxies...
Distributions of the rest-frame MIR–radio spectral index $\alpha$, the ratio of the 12 $\mu$m luminosity (left panel) or 22 $\mu$m luminosity (right panel) to the 1.4 GHz luminosity. The distributions of $\alpha$ for AGNs on Branch A (black histograms) may be compared to those of mass-matched SF galaxies (red histograms). The median values of each distribution are marked with appropriate red or black circular points at the top of each panel.

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

are shown, estimated using an ordinary-least-squares (OLS) bisector algorithm. Only the AGNs from Branch A that were successfully matched to inactive galaxies are used in the regression analysis. The relative trends for both sets of objects can be compared at a glance.

In the right panel of Figure 6, we include as well the ridgeline of the FIR–radio correlation found among SF galaxies (e.g., Condon 1992; Sargent et al. 2010), extrapolated to rest-frame 22 $\mu$m using the SF templates of Chary & Elbaz (2001). The increased contribution of warm dust in the MIR at the transition between normal SF galaxies and luminous IR galaxies (LIRGs), as modeled by Chary & Elbaz (2001), is responsible for the kink in the shape of this line in this diagram; real galaxy populations likely show a smoother relationship. Inactive SF galaxies and AGNs on Branch A scatter quite symmetrically about the FIR–radio correlation, implying that the 22 $\mu$m luminosity of both is largely produced by SF-heated dust.

A closer look at the ratio of MIR to radio luminosity brings out the differences at 12 $\mu$m and 22 $\mu$m. We define an MIR–radio spectral index $\alpha = L_\nu[\text{MIR}]/L_\nu[1.4 \text{ GHz}]$, where the MIR = 12 $\mu$m or 22 $\mu$m. In Figure 7, we compare the $\alpha$ distributions of stellar mass matched SF inactive galaxies and AGNs on Branch A. The SF galaxies always show a narrower distribution than the AGNs. While the median $\alpha$ values for both sets of objects are approximately the same at 22 $\mu$m, differing by 0.06 dex, the AGNs are weaker compared to the SF galaxies at 12 $\mu$m by 0.29 dex. We discuss possible reasons for these differences in Section 5. Since $L_{22}$ is more consistent with an origin in SF, we use only 22 $\mu$m measurements in further tests.

As a final test of the relationship between Branch A and SF, we plot the location of the AKARI 90 $\mu$m detected sources on the $L_{12}$–$L_{1.4}$ diagram for AGNs (Figure 8). Given the depth of the AKARI/FIS survey, the hosts of these AGNs must be forming stars at a modest rate of several to tens of $M_\odot$ yr$^{-1}$. Every single AKARI-detected source lies on Branch A, which strongly reinforces the conclusion that this branch marks the location of SF host galaxies in the MIR–radio plane.

4.2. The Relation between $D_n4000$ and MIR Luminosity

The optical spectral index $D_n4000$, sensitive to the strength of the 4000 Å break, is a good measure of the light-weighted specific SFR (sSFR) of galaxies (Brinchmann et al. 2004). If the two branches identified above do indeed correspond to AGNs with different levels of ongoing SF in their hosts, one may expect a difference in the $D_n4000$ distributions of AGNs in the two branches. This is tested in Figure 9, where we plot $D_n4000$ against $L_{22}/M_*$.

Figure 9 shows a strong anticorrelation between $D_n4000$ and $L_{22}/M_*$. If the 22 $\mu$m luminosity is determined primarily by the SFR of the AGN hosts, then $L_{22}/M_*$ will be proportional to the sSFR and, therefore, tracked by $D_n4000$. Indeed, we find a strong anticorrelation between $D_n4000$ and $L_{22}/M_*$. In addition, objects from the two branches are reasonably well separated in this diagram. Branch B AGNs have a higher $D_n4000$, clustering around a value of 1.9 at which the sensitivity of $D_n4000$ as a tracer of stellar age saturates in old stellar populations. In contrast, objects in Branch A show typically much smaller $D_n4000$, peaking around a value of 1.4, and form much of the ridgeline of the correlation in the figure. Clearly, the separation of AGNs into two branches also largely separates them by sSFR.
In addition to the AGNs, we also plot the modal trend between $D_{n,4000}$ and sSFR from Brinchmann et al. (2004) as a green line in the figure. We have used the SED library of Chary & Elbaz (2001), along with the relation between SFR and $L_{22}$, to convert between SFR and $L_{22}$ and place the Brinchmann et al. (2004) line on this figure. At a given $L_{22}/M_*$, AGNs have a higher $D_{n,4000}$ than those of SF galaxies, irrespective of the branch to which they belong. We have checked that galaxies from our SF inactive control sample lie along the Brinchmann et al. (2004) line, verifying that the offset we see for AGNs is not due to systematic differences in the estimation of the SFR from $L_{22}$ (Brinchmann et al. 2004) calibrate SFRs from Hα. Since we have shown that the $L_{22}$ of AGNs and SF galaxies are not systematically different, certainly not at the level of $\approx 0.3$ dex needed to reconcile the AGNs and SF trends in Figure 9, this would suggest that AGNs have higher $D_{n,4000}$ than SF galaxies of similar stellar mass, or, alternatively, AGNs show a lower sSFR than SF galaxies. At face value, this is puzzling, given the similarity in the galaxy integrated SFRs of the two populations as traced by their 22 μm luminosity distributions. However, the difference makes more sense if we consider the aperture-related selection effects of SDSS spectroscopic samples. BPT selection of AGN-dominated systems systematically selects against objects with strong SF in the SDSS fiber aperture, while the selection of pure SF galaxies selects for strong central SF. Against the backdrop of the older bulge stellar populations found in massive galaxies, this selection effect will naturally lead to lower measured sSFRs for the AGNs.

4.3. Radio-loudness and Its Relation to the Branches

Further examination of Figure 3 reveals an interesting connection between the strength of radio emission and the division into branches. Consider the small number of sources with $L_{1.4}>10^{24}$ W Hz$^{-1}$, which are too radio-loud to be powered by even the most luminous SF galaxies. We find that most of these sources lie on Branch B, with relatively few radio galaxies lying on Branch A. We can explore this connection more robustly by plotting $D_{n,4000}$ against the specific radio luminosity ($L_{1.4}/M_*$) of our AGNs (Figure 10). This plot was first proposed in Best et al. (2005) and recalibrated in Best & Heckman (2012) as a way to identify sources with a strong radio excess over that produced by SF. Pure star-forming galaxies with a range of SF histories lie along a fixed locus in this diagram and below the dashed line in Figure 10. Above the line, sources may be treated as radio-loud.

As one may see at a glance, sources on Branch A lie primarily in the radio-quiet, SF-dominated part of the diagram, with only 12% lying above the dashed line. Sources on Branch B straddle the line, but most are in the radio-loud part of the diagram. As hinted by Figure 3, radio-loud AGNs in our sample lie mostly on Branch B. The scatter about the separation line depends on a complex set of factors such as the biases of BPT AGN selection (Section 2.1.1) and SDSS aperture effects, since $L_{1.4}$ tracks the galaxy integrated radio luminosity, while $D_{n,4000}$ only traces the inner stellar populations. However, we take the broad separation of the branches in this diagram as evidence that radio-loud AGNs lie preferentially on Branch B, while Branch A is preferentially populated by radio-quiet SF hosts.

The dearth of SF signatures and MIR weakness in powerful radio galaxies (with $L_{1.4}>10^{26}$ W Hz$^{-1}$) is well known from previous studies (e.g., Ogle et al. 2006; Shi et al. 2007; Dicken et al. 2012). Comparisons of radio-loud quasars and radio galaxies also indicate high MIR optical depths in the latter (Leipski et al. 2010) and boosted non-thermal emission in the former (Cleary et al. 2007), both of which must be considered in a complete picture of the relative MIR-to-radio properties of radio-loud systems.

4.4. AGN-heated Dust in the MIR

Until now, our tests have connected SF and the emission of AGN hosts in the long-wavelength MIR. However, given the expected prominence of AGN-heated dust at these wavelengths,
it is important as well to constrain the contribution from the AGNs.

4.4.1. The \( L_{22}-L_{[O\text{iii}]} \) Relation in AGNs and Star-forming Galaxies

A simple test for the influence of the AGNs in the MIR is shown in the left panels of Figure 11, where we plot \( L_{22} \) against \( L_{[O\text{iii}]} \) for all WISE-detected AGNs, including those that are not detected in the FIRST survey. In AGN-dominated galaxies, the \([O\text{iii}]\) emission lines are a good measure of the intrinsic luminosity of the AGNs, since they originate in the highly ionized NLR. Therefore, and also for consistency with the compilation of \([O\text{iii}]\) luminosities discussed below, we present our analyses using uncorrected \( L_{[O\text{iii}]} \). However, we have tested our results using a fixed extinction of \( A_V = 0.8 \), the typical value estimated for the brighter AGNs in our sample. The basic conclusions remain unchanged.

We find that AGNs show a good correlation between \( L_{[O\text{iii}]} \) and \( L_{22} \). The correlation suggests either that the AGN contributes significantly to the luminosity of host galaxies at 22 \( \mu \)m or, alternatively, that the total SF in AGN-dominated galaxies tracks nuclear activity. Similar results have been shown before for AGN-dominated galaxies from the SDSS using other tracers of the SFR, such as \( D_n=4000 \) (Netzer 2009). We discuss these alternatives in more detail in Section 5.3.

Note that purely SF galaxies from our control sample also show a strong correlation between \( L_{[O\text{iii}]} \) and \( L_{22} \), as demonstrated in the right panel of Figure 11. The slope of this correlation is similar to that shown by AGNs, but it is shifted toward lower \( L_{[O\text{iii}]} \) by 1.7 dex. Given the characteristic flux limits of the SDSS spectra, which are translated to luminosity limits at different redshifts and plotted as dashed lines in the figure, one concludes that the correlation seen in SF galaxies is mostly shaped by Malmquist bias. At progressively higher redshifts, only galaxies luminous both at 22 \( \mu \)m and in \([O\text{iii}]\) will be selected, tightening the correlation. Nevertheless, we can use our sample to constrain the degree to which emission from SF may contribute to the \([O\text{iii}]\) \( \lambda 5007 \) emission in the AGNs. We construct an envelope that contains 80% of SF galaxies, shown as a solid line in the figure, which we compare below to the location of the AGNs on this diagram.

4.4.2. The Intrinsic MIR Luminosity of AGNs

Before we can embark on this exercise, we require a predictor for the intrinsic MIR luminosity of the AGNs that we can compare to the measured MIR luminosity of the WISE-detected sources. Many studies have used MIR spectroscopy to empirically investigate the relation between nuclear power and the MIR continuum or PAH luminosity in nearby and distant AGNs (e.g., Lutz et al. 2004; Shi et al. 2007; Diamond-Stanic & Rieke 2010; LaMassa et al. 2010). Most studies rely on fairly large apertures in the MIR—for example, with the Spitzer IRS spectrograph, the workhorse for most of such studies, typical apertures used to extract spectra correspond to scales of a few to several kiloparsecs. The contribution of SF-heated dust to the long-wavelength MIR in such spectra could be substantial. Therefore, we turn to a high-resolution (sub-arcsec) photometric study of the MIR emission in local AGNs using narrowband imaging from the VISIR instrument on the Very Large Telescope (Gandhi et al. 2009; Asmus et al. 2011). These small-scale observations greatly limit host galaxy dilution and isolate, as best as currently possible, the AGN-heated torus emission from the nucleus. Having said this, in some cases the VISIR measurements may still have a substantial SF contribution from starbursts on tens of parsecs scales (Asmus et al. 2011).

For a set of \([O\text{iii}]\) \( \lambda 5007 \) emission line fluxes, we employ the compilation of Whittle (1992), which uses a coherent methodology to account for aperture losses, bringing consistency to the varied nature of spectroscopic studies of AGNs in the local universe. Whittle (1992) only provide observed line fluxes, uncorrected for extinction, but since we use uncorrected \( L_{[O\text{iii}]} \) in our full analysis, we directly adopt these measurements.
Combining 12.3 $\mu$m luminosities with $L_{[\text{O\,iii}]}$ for Seyferts in common to the two data sets, we establish a tight correlation between these quantities (Figure 12), which we fit using an OLS bisector regression algorithm. The correlation is tighter for the more luminous AGNs, but the scatter increases at lower luminosities, possibly due to a higher level of SF contamination among such systems. Nevertheless, we use our best-fit relationship to estimate a 12.3 $\mu$m luminosity for an AGN given $L_{[\text{O\,iii}]}$:

$$L_{12.3} = 1.02 L_{[\text{O\,iii}]} + 1.24.$$  

(1)

Armed with this relationship, we construct a set of hybrid IR templates of AGNs embedded in star-forming hosts. The average MIR template of Type I AGNs from Mor & Netzer (2012) is combined with the SF SED library of Chary & Elbaz (2001), scaling the AGN template using Equation (1) to cover a range of nominal AGN luminosities in the range $L_{[\text{O\,iii}]} = 10^{38–43}$ erg s$^{-1}$. The resulting set of hybrid templates span a wide range in MIR AGN dominance, from sub-percentile to 100% AGN emission at 22 $\mu$m. There is considerable scatter of both real galaxy and AGN SEDs about our adopted templates, so these models are not exact for any individual object, but will serve as a guide to the typical behavior of star-forming AGN hosts with varying degrees of nuclear emission.

4.4.3. The Star Formation/AGN Mixing Diagram

In Figure 13, we again plot $L_{[\text{O\,iii}]}$ against $L_{22}$, now only for sources with both FIRST and WISE detections, i.e., the subsample that can be classified into branches. The distribution of AGNs is shown as a density map, but now splitting the AGNs by panel into the two branches. Overplotted on the left panel over the distribution for Branch A is the loci of the hybrid templates, shown as dashed lines colored by SF-powered IR luminosity. These lines are not plotted in the right panel since the MIR luminosity of the objects in Branch B probably does not arise from recent SF.

The hybrid template loci have a characteristic shape: as the AGN luminosity in a particular hybrid increases, it moves along a track of increasing $L_{[\text{O\,iii}]}$ at a fixed $L_{22}$ until the AGN fraction at 22 $\mu$m starts to approach unity. At this point, all loci bend onto the pure AGN line (dashed line in both panels). Naturally, the characteristic AGN $L_{[\text{O\,iii}]}$ at the turnover is a function of the IR luminosity of the SF template. Interestingly, among the LIRGs (with $L_{\text{IR}} > 10^{11}$ erg s$^{-1}$), it is possible to conceal the MIR emission of quite a luminous AGN, with $L_{[\text{O\,iii}]}$ as high as $10^{11}$ erg s$^{-1}$ ($L_{\text{bol}} \approx 4 \times 10^{44}$ erg s$^{-1}$, based on the bolometric correction of Heckman et al. 2004).

A key point to take from Figure 13 is that the $L_{22}$ of pure AGN templates is quite close to the observed $L_{22}$ for the AGNs, given their $[\text{O\,iii}]$ luminosities. Disentangling SF and nuclear components of the MIR luminosity in these AGNs is therefore not trivial. Nevertheless, we proceed given our assumptions about the intrinsic AGN luminosity and the SEDs of AGNs and SF components, and we discuss some of the complexities in Section 5.

AGNs from both branches show a correlation between $L_{22}$ and $L_{[\text{O\,iii}]}$. In detail, there are some differences between the behavior of the two branches in the diagram. The characteristic $L_{[\text{O\,iii}]}$ of AGNs in Branch B is lower than that for Branch A, a consequence primarily of the larger fraction of low-luminosity LINERs in Branch B. The ridge line of the Branch B distribution lies closer to the pure AGN locus than that of Branch A, as can be judged from the sequence of large colored circular points plotted in the left panel of the diagram. The points show the location on the template loci where the AGN accounts for 15% of $L_{22}$, chosen to run through the peak of the Branch A distribution. Clearly the sources on Branch B are more AGN dominated in the MIR, even though they contain less luminous AGNs. Having said this, we see that the ridge line of the Branch B distribution is still slightly offset from the pure AGN locus, most clearly for the LINERs. This could reflect the presence of additional sources of weak MIR emission such as cirrus heating by evolved stars (Sauvage & Thuan 1992; Calzetti et al. 1995; Groves et al. 2012) or the synchrotron tail from relativistic particles (e.g., Yuan 2007), which only become prominent in low-luminosity systems with minimal SF and AGN heating.

In both panels of Figure 13, we use different colored contours to show the location of Seyferts and LINERs in each panel. As expected, Seyferts have higher $L_{[\text{O\,iii}]}$ than LINERs in both branches. In fact, some LINERs on Branch A are weak enough in $[\text{O\,iii}]$ to place them in the region occupied by the star-forming galaxies. A substantial fraction of the line emission in such systems could arise from H II regions. In addition to this, the LINERs on Branch A show a weaker correlation between $L_{[\text{O\,iii}]}$ and $L_{22}$ than the Seyferts on the same branch. Their typical location on the diagram is also further away from the AGN line than the Seyferts, indicating that such star-forming LINERs are even more dominated at 22 $\mu$m by SF-heated dust.

It is worth noting that the median $L_{[\text{O\,iii}]}$ of LINERs on Branch A and Branch B are similar despite an order of magnitude difference in their median $L_{22}$. This also highlights the conclusion that the separation of the AGN population into branches is mostly governed by processes unrelated to their direct nuclear emission.

5. DISCUSSION

5.1. Summary of Empirical Results

The patterns exhibited by AGNs in Figures 3 and 4 strongly suggest the existence of distinct populations (branches) of active galaxies, differentiated by their MIR-to-radio properties. Intimately connected to the nature of the branches is the origin of the integrated (i.e., galaxy-wide) MIR emission of the AGNs. Before proceeding with an interpretive discussion, we summarize what we have learned about the branches from the various tests performed above.
Figure 13. [O iii] $\lambda$5007 luminosity ($L_{[O\,iii]}$) versus rest-frame 22 $\mu$m luminosity ($L_{22}$) of SDSS emission line selected AGNs on Branch A (left panel) and Branch B (right panel), plotted as a density map. A sinh$^{-1}$ stretch is applied to the map to enhance low-density regions. In each panel, the locations of Seyferts (blue contours) and LINERs (red contours) are also shown. The solid black line is the 80% envelope of SF galaxies (see Figure 11), while the dashed black line shows the location of a pure AGN template on this diagram. The colored dashed lines in the left panel show the loci of hybrid templates of star-forming galaxies containing AGNs, with an SF-powered IR luminosity indicated by the color bar at right. As the AGN luminosity traced by $L_{[O\,iii]}$ reaches a level where it starts to dominate the MIR luminosity of a hybrid template, the loci transition from a fixed $L_{22}$ to a sloped line on which AGN-dominated systems lie. The colored dashed lines in the left panel show the loci of hybrid templates of star-forming galaxies containing AGNs, with an SF-powered IR luminosity indicated by the color bar at right. As the AGN luminosity traced by $L_{[O\,iii]}$ reaches a level where it starts to dominate the MIR luminosity of a hybrid template, the loci transition from a fixed $L_{22}$ to a sloped line on which AGN-dominated systems lie. The colored dashed lines in the left panel show the loci of hybrid templates of star-forming galaxies containing AGNs, with an SF-powered IR luminosity indicated by the color bar at right. As the AGN luminosity traced by $L_{[O\,iii]}$ reaches a level where it starts to dominate the MIR luminosity of a hybrid template, the loci transition from a fixed $L_{22}$ to a sloped line on which AGN-dominated systems lie. The colored filled circles mark the location on the hybrid template loci where the AGN accounts for 15% of $L_{22}$. Since the MIR in AGNs on Branch B is not governed by star formation, hybrid templates are not plotted in the right panel. (A color version of this figure is available in the online journal.)

Sources on Branch A have higher absolute MIR luminosities than those on Branch B (Figure 3); describe a steep trend in MIR–radio space, shared with SF galaxies (Figure 6); account for 95% of Seyfert AGNs and 50% of LINERs (Figure 4); are consistent with the median MIR–radio relationship of SF galaxies at 22 $\mu$m (Figure 7); are offset low from the median MIR–radio relationship of SF galaxies at 12 $\mu$m by $\approx 0.3$ dex (Figure 7); have a larger scatter in their MIR–radio distribution compared to SF galaxies (Figure 7); include all FIR-bright AGN hosts with substantial SF (Figure 8); have a low median $D_n$4000 $\approx 1.4$ (Figure 9); are largely radio-quiet, with radio luminosities consistent with an SF origin (Figure 10); and are consistent with typically low AGN contributions at 22 $\mu$m of 15% (Figure 13).

In comparison, sources on Branch B have lower absolute MIR luminosities than those on Branch A (Figure 3); describe a shallow trend in MIR–radio space, consistent with uncorrelated scatter modulated by redshift-dependent MIR luminosity limits (Figure 5); account for 50% of LINERs and only 5% of Seyferts (Figure 4); lie well off the MIR–radio relationship of SF galaxies (Figure 6); have a higher $D_n$4000 $\approx [1.6, 2.0]$ (Figure 9); account for most radio-loud AGNs (Figure 10); and are more AGN dominated in the MIR than Branch A (Figure 13).

5.2. Origin of the Branches in the MIR–Radio Plane

Our investigation has revealed evidence for a mixture of different heating mechanisms for dust in the hosts of AGNs: SF, nuclear light, and possibly a contribution from cirrus heated by the UV background in galaxies. Here we critically examine the role of these mechanisms in the nature of the branches. First, we consider two simplified alternate explanations, which allow us to conceptually explore the assumptions and conclusions one may draw from the empirical analyses of the last two sections. Then we consider the consequences of combining these alternatives toward a more realistic and nuanced picture of the MIR properties of AGNs.

![Figure 14](image.png)

Figure 14. Schematic descriptions of the two scenarios for the origin of the branches in the MIR–radio plane outlined in Section 5. The two branches are labeled “A” and “B” as from Figure 3. The “dim” population that lies below the joint WISE and FIRST detection limits is designated with a question mark, signifying our lack of knowledge of their true MIR–radio relationship. Scenario 1, denoted in blue, assumes that star formation purely governs the location of AGN hosts on Branch A. Scenario 2, denoted in red, assumes that pure AGN emission governs all patterns on the MIR–radio plane. See Section 5.2 for more details and a discussion. (A color version of this figure is available in the online journal.)

We begin by outlining two extreme and opposite positions: (1) the 12–22 $\mu$m luminosity of AGNs on Branch A is dominated by SF-heated dust, or (2) the 12–22 $\mu$m luminosity of AGNs on both branches is dominated by AGN-heated dust. These scenarios are outlined schematically on the MIR–radio plane in Figure 14. In both cases, we assume that there is a substantial population of non star-forming, low-luminosity AGN hosts, most of which lie below the joint SDSS, WISE, and FIRST detection limits. We term this the “dim” population, signifying their weakness in both SF and nuclear emission. We do not
speculate here on the MIR–radio relationship of the dim population, representing them instead as a cloud with a question mark signifying our lack of knowledge. Only a small fraction, the tip of the iceberg, are detected in our sample, perhaps due to higher than average levels of dust in their hosts heated by the AGN or the diffuse UV field, or possibly shocks from radio jets. These constitute the systems on Branch B. Fully detected AGNs lie within the quadrant delineated by the axes in Figure 14.

5.2.1. Star Formation as the Origin of the Branches

This scenario is represented using blue arrows and lines in Figure 14. In addition to the dim population described above, there is a set of AGNs found in galaxies with widespread SF. These galaxies will have elevated IR and radio luminosities over the dim population and lie along the correlation between IR and radio continuum luminosities. They constitute Branch A.

Support for this scenario comes from the various relationships between the nature of the branches and measures of SF. Objects on Branch A show a tight correlation between $L_{22}$ and $D_n4000$, while most Branch B AGNs lie in evolved systems (Section 4.2). FIR-bright AGNs all lie on Branch A (Section 4.1). But the most crucial constraint comes from the correspondence between the $L_{22}$–$L_{1.4}$ relationship of Branch A and that of pure SF galaxies. This correlation is widely understood to be set by the close relationship between the non-thermal output from supernovae and the UV emission from young stars, reprocessed to the IR. If AGN-heated dust significantly affected $L_{22}$, we would have seen an offset toward higher 22 $\mu$m luminosities among the AGNs, which we do not observe, except perhaps among some of the brightest AGNs in our sample. This, as well as the constraints from hybrid templates and the radio-loudness test, suggests that the MIR luminosity, as well as the radio luminosity, of most AGNs on Branch A is dominated by SF.

Interestingly, the 12 $\mu$m luminosity of AGNs on Branch A is too low at a given $L_{1.4}$ to lie consistently with SF galaxies. In other words, AGNs on Branch A have redder W3–W4 colors than SF galaxies of the same (radio-based) SFR. Two effects may account for this. One is the suppression of PAH excitation or the destruction of PAH grains in AGN-dominated systems, as suggested by recent Spitzer/IRS spectroscopic studies of large samples of SDSS AGNs (LaMassa et al. 2012). Additionally, strong 10 $\mu$m Si absorption troughs, frequent in Type II AGNs (Shi et al. 2006; Hao et al. 2007), could contribute to the offset.

5.2.2. AGN Emission as the Origin of the Branches

In Figure 14, red arrows and lines represent the scenario where the hot-dust emission from the AGN torus ultimately sets the patterns in the MIR–radio plane. For this to be the case, our estimate of the intrinsic MIR AGN luminosity would have to be systematically in error, to account for the $\sim$0.7 dex in $L_{22}$ needed to reconcile the ridgeline of the AGN trend with the AGN-dominated line in Figure 13. This estimate is based on high-resolution 12 $\mu$m photometry of very nearby AGNs combined with the best current knowledge of their intrinsic MIR SEDs. It may be that the low- to moderate-luminosity AGNs in our sample have a redder mean MIR SED than existing studies currently suggest, leading to a more luminous 22 $\mu$m luminosity than we apply to our hybrid templates. This is supported by studies of the typical SEDs of low-luminosity AGNs (e.g., Ho 2008), though at the higher AGN luminosities among our sample, the Mor & Netzer (2012) SED should be accurate.

In this scenario, the two branches represent a bimodal distribution of AGNs with different levels of radio output relative to their thermal (accretion disk) output. This is akin to the well-known “radio-loud/radio-quiet” dichotomy (e.g., Sikora et al. 2007). Objects on Branch B are low luminosity AGNs that span a range in radio luminosity and may be fueled by so-called hot-mode accretion, while objects on Branch A, which contain most luminous AGNs and Seyferts, have a more definite relationship between their thermal and non-thermal output and are fueled mostly by “cold-mode” accretion (Best & Heckman 2012).

An AGN-dominated MIR SED may help explain the redder W3–W4 color of AGN hosts compared to SF galaxies, since pure AGN SED templates, such as that of Mor & Netzer (2012), which lack PAH emission bands, are usually redder than the templates of weakly SF galaxies. Having said this, SF-related features, such as low-ionization emission lines and PAH bands, are known to be fairly common in the MIR spectra of AGN hosts (e.g., Weedman et al. 2005; Buchanan et al. 2006; Wu et al. 2009), so pure AGN-dominated MIR SEDs in all systems do not have much empirical support. Earlier studies have reported a higher average AGN contribution to the MIR than we find (e.g., >45% among Type II AGNs at 19 $\mu$m in Tommasin et al. 2010), but this is almost certainly because most existing spectroscopic samples target rather nearby systems and sample only the inner few kiloparsecs of the host galaxy (Figure 2), missing most of the continuum and PAH luminosity emitted by SF on larger galactic scales.

Besides this, an AGN-dominated scenario would still have to explain the close relationships found between the branches and SF indicators, as well as the conspiracy that the $L_{22}$–$L_{1.4}$ of the AGNs on Branch A, set only by the intrinsic AGN output in this picture, overlaps that of pure SF galaxies. The processes that govern the relative non-thermal output in AGNs (e.g., the Poynting flux from the magnetosphere of an SMBH) are drastically different from those that set the non-thermal output of SF regions (i.e., shock acceleration in supernova remnants), so a common slope and normalization for the trends in the MIR–radio plane are very unlikely.

5.2.3. A Mixed Origin

In our analysis of the $L_{[01]}$–$L_{22}$ diagram, we show that both SF and AGN-heated emission are expected to produce luminosities close to the values seen among real AGNs. This suggests that the MIR luminosity of AGNs, especially those on Branch A, is likely a mixture of AGN-heated and SF-heated components. The investigation using hybrid templates suggests that the component from SF probably dominates by a small margin, accounting for, on average, $\sim$85% of $L_{22}$. However, the AGN-heated component sets a floor to the MIR luminosity—even if the SFR of an AGN host galaxy is low, its total MIR luminosity cannot drop below the level set by the nuclear component.

A mixed origin for Branch A could contribute to the broader width of the $\alpha(22$ $\mu$m–1.4 GHz) distribution for AGNs on this branch (Figure 7). The SFR of the host galaxy places a particular AGN at a particular location on the locus of SF galaxies in the MIR–radio plane. AGN activity can potentially boost both the MIR and radio luminosity over the level set by the SFR. If the AGN is radio weak but IR bright, it will scatter the system above the Branch A ridgeline. Alternatively, if the AGN is relatively radio bright, it will scatter the system below the ridgeline by increasing its $L_{1.4}$ without changing its MIR luminosity significantly. Differing combinations of radio and MIR luminosity will scatter objects off the SF locus, leading to the broader distribution we see among AGNs. The slight
asymmetry in the shape of the $\alpha(22 \mu m-1.4 GHz)$ distribution may indicate that the scatter from enhanced radio emission is larger than the scatter from AGN MIR emission. However, further careful study is necessary to test this notion.

5.3. The Star-forming Properties of AGNs

One of the most interesting results from our study is that 95% of SDSS/WISE/FIRST Seyfert galaxies lie on Branch A, while lower luminosity LINERs are more frequently on Branch B. We have shown that most objects on Branch A have considerable ongoing SF. This implies a relationship between the ionization of AGN emission lines and SF in their hosts.

The characteristic low $L_{[\text{O} \text{III}]}$ of LINERs imply that they are low-luminosity AGNs. Studies have shown that they are typically in massive, evolved hosts with low levels of SF (e.g., Ho 2008; but see Tommassin et al. 2012). An examination of the left panel of Figure 4 suggests that a fraction of LINERs have ongoing SF, though their typical SFRs, as tracked by their MIR luminosity on Branch A, are lower than in Seyferts. Combined with the fact that a large fraction of LINERs lie on Branch B, our results add support to the view that LINERs are found mostly in quiescent or quenching hosts.

On the other hand, the very high fraction of Seyferts on Branch A is evidence that most Seyferts are in actively star-forming host galaxies. This is consistent with GALEX-based UV studies that show that so-called bright AGNs in the SDSS are found among fairly normal SF galaxies (Salim et al. 2007). Since the ionization state of AGNs is strongly correlated with $L_{[\text{O} \text{III}]}$, such bright emission line selected AGNs are essentially all Seyferts. Bright AGNs are known to have lower $D_{\text{SF}}4000$ than lower luminosity AGNs, indicative of younger mean stellar ages (Kaufmann et al. 2003a). Morphological studies also reveal that Seyfert hosts are generally in massive galaxies with disks and active SF, while early-type galaxies hosting bright AGNs frequently show anomalously blue colors suggestive of ongoing SF (e.g., Schawinski et al. 2010). Studies of X-ray selected AGNs from deep extragalactic survey fields also show a high frequency of SF host galaxies, compared to similarly massive inactive galaxies (Silverman et al. 2009; Rosario et al. 2013). This suggests that radiatively efficient nuclear activity, which powers X-ray and emission-line bright AGNs, is associated with ongoing SF in the host galaxy. This can be explained by many diverse models, such as connected nuclear starbursts and AGN fueling (Davies et al. 2007), merger-induced AGN activity (Hernquist 1989), accretion from stellar mass loss (Ciotti & Ostriker 2007), or their combinations. Alternatively, since both efficient nuclear fueling and SF rely on the same supply of material, namely, cold gas, the connection seen here may be simply governed by the stochastic availability of this fuel, rather than any real causal link between the AGN and galaxy-wide SF (e.g., Rosario et al. 2013).

The correlation between $L_{[\text{O} \text{III}]}$ and $L_{22}$ for objects on Branch A (left panel of Figure 13) also seems to suggest a correlation between the global SFR of AGNs and their nuclear luminosity. However, as described in Section 2.1.1, an important selection between the global SFR of AGNs and their nuclear luminosity is larger than the scatter from AGN MIR emission. However, future careful study is necessary to test this notion.

6. CONCLUSIONS

We investigate the trends between the radio and long-wavelength MIR luminosities of narrow-line (Type II) emission line selected AGNs from the SDSS, which reveals characteristic patterns in the MIR–radio plane, suggestive of two distinct populations or “branches.” Building on the substantial ancillary data from the SDSS, as well as AKARI FIR photometry, we devise various tests to help unveil the properties of the two branches. Objects on Branch A are generally radio-quiet, have younger central stellar populations, and exhibit an IR-radio relationship consistent with that of normal inactive SF galaxies, though with suppressed luminosity at 12 $\mu m$. Objects on Branch B account for most radio-loud AGNs, have evolved central stellar populations, and lie well off the location of SF galaxies on the MIR–radio plane, implying that their MIR emission is unrelated to SF. These tests demonstrate that the galaxy-integrated MIR luminosity of AGNs on Branch A arises primarily from dust heated by ongoing SF. A correlation between the $[\text{O} \text{III}],5007$ luminosity and the MIR luminosity suggests a possible relationship between SF and nuclear emission, but important selection effects inherent to emission line selected AGNs may also account for some or all of the trend. We highlight the result that the majority of Seyfert galaxies lie on (or are consistent with lying on) Branch A, which suggests a connection between the processes that govern SF and the fueling of radiatively efficient AGN activity. The MIR–radio plane is a useful tool in studies of the SF and accretion properties of AGNs over a range of nuclear luminosities.

We thank Hagai Netzer and Li Shao for useful discussions. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This research also employs observations with AKARI, a JAXA project with the participation of ESA.

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Asmus, D., Gandhi, P., Smette, A., Höning, S. F., & Duschl, W. J. 2011, A&A, 536, A36
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bennert, N., Jungwiert, B., Komossa, S., Haas, M., & Chini, R. 2006, A&A, 456, 953
Best, P. N., & Heckman, T. M. 2012, MNRAS, 421, 1569
Best, P. N., Kaufmann, G., Heckman, T. M., & Ivezic, Z. 2005, MNRAS, 362, 9
Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151
Buchan, C. L., Gallimore, J. F., O'Dea, C. P., et al. 2006, AJ, 132, 401
Calzetti, D., Bohlin, R. C., Kinney, A. L., Storchi-Bergmann, T., & Heckman, T. M. 1994, ApJ, 443, 136
