Identifying Radio-active Galactic Nuclei among Radio-emitting Galaxies

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Abstract

Basing our analysis on ROGUE I, a catalog of over 32,000 radio sources associated with optical galaxies, we provide two diagnostics to select the galaxies where the radio emission is dominated by an active galactic nucleus (AGN), referred to in the paper as radio-AGNs. Each of these diagnostics can be applied independently. The first one, dubbed MIRAD, compares the flux $F_W$ in the $W_3$ mid-infrared band of the Wide-field Infrared Survey Explorer telescope, with the radio flux at 1.4 GHz, $F_{1.4}$. MIRAD requires no optical spectra. The second diagnostic, dubbed DLM, compares the 4000 Å break strength, $D_0(4000)$, with the radio luminosity per unit stellar mass. The DLM diagram has already been used in the past, but not as stand-alone. For these two diagrams, we propose simple, empirical dividing lines that result in the same classification for the objects in common. These lines correctly classify as radio-AGN 99.5% of the extended radio sources in the ROGUE I catalog, and as star-forming galaxies 98%–99% of the galaxies identified as such by their emission-line ratios. Both diagrams clearly show that radio-AGNs are preferentially found among elliptical galaxies and among galaxies hosting the most massive black holes. Most of the radio sources classified as radio-AGNs in the MIRAD or DLM diagrams are either optically weak AGNs or retired galaxies.

Unified Astronomy Thesaurus concepts: Surveys (1671); Astronomical methods (1043); Catalogs (205); Radio galaxies (1343); Radio active galactic nuclei (2134)

1. Introduction

One of the requirements for the study of nuclear activity in galaxies and in particular of the genesis and nature of radio jets that are present in only a minority of active galactic nuclei (AGNs) is the availability of large and complete multi-wavelength catalogs. In the past two decades several such catalogs have been produced by cross-matching optical surveys, especially the Sloan Digital Sky Survey (SDSS; York et al. 2000), and radio surveys, especially the First Images of the Radio Sky at Twenty cm (FIRST; White et al. 1997) and the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) (e.g., McMahon et al. 2002; Sadler et al. 2002; Best et al. 2005a; Kimball & Ivezic 2008; Best & Heckman 2012; Banfield et al. 2015; Williams et al. 2019; Sabater et al. 2019; Kozieł-Wierzbowska et al. 2020).

The catalog of Kozieł-Wierzbowska et al. (2020) (ROGUE I, for “Radio sources associated with Optical Galaxies and having Unresolved or Extended morphologies”) as it is published makes no claim about the nature of the radio emission and contains radio-emitting AGNs (both jetted and non-jetted, according to the nomenclature proposed by Padovani 2016, 2017) and galaxies whose radio emission is related to recent star formation. While galaxies that clearly present resolved radio structures, such as jets and lobes, are known to inhabit an AGN, the question is more subtle (and difficult) for unresolved radio sources. A similar situation occurs with the ongoing LOFAR Two-Metre Sky Survey (LoTSS) by Shimwell et al. (2017), except that, in this case, optical spectra are not available for most sources. The aim of this paper is to present a simple way to distinguish radio sources powered by an AGN from those powered by star formation and to discuss the global properties of radio-emitting galaxies. We must mention, however, that many galaxies that have an optical signature of an AGN also present some level of radio emission. This radio emission can be produced by various, often coexisting mechanisms, like star formation, AGN-driven winds, or accretion disk coronal activity (e.g., Zakamska & Greene 2014; Raginski & Laor 2016; Panessa et al. 2019). Such sources, often referred to as radio-quiet (or non-jetted) AGNs, are present among galaxies studied in this paper but do not belong to the class of what we call radio-active AGNs, sometimes referred to as jetted AGNs. If the optical spectra do not have high signal-to-noise ratios ($S/N$) in the emission lines characteristic of optical AGNs, the “optical AGN activity” can even be buried in the noise. In the diagrams we present, such objects are found in the same zone as SF galaxies. To distinguish them from pure SF galaxies, one would need to consider high-quality optical spectra and/or higher-resolution radio maps.

Different groups in the past have used a conjunction of several criteria to separate radio-AGNs from star-forming (SF) galaxies in samples of radio sources, e.g., Best & Heckman (2012), whose catalog matched SDSS DR7 galaxies with NVSS and FIRST radio sources using an automatic procedure and going down to 5 mJy, and Sabater et al. (2019), who base their sample on the first release of LOFAR data (Shimwell et al. 2019) that go much deeper in radio. We prefer using just one

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criterion, which results in a simpler classification and makes it easier to understand selection biases in the subsequent analyses.

For samples of radio sources for which no optical spectra are available, we use the mid-infrared (MIR) data from the Wide-field Infrared Survey Explorer (WISE) survey (Wright et al. 2010) to distinguish radio emission linked with star formation from radio emission produced by AGNs. For samples of radio sources for which spectra of the host galaxies exist, we show that the diogram of the 4000 Å break strength, $D_4(4000)$, versus radio luminosity per unit stellar mass, $L_{1.4}/M_*$, hereafter the DLM diagram, first introduced by Best et al. (2005b) and revised several times (see Sabater et al. 2019), is on its own fully adequate to sieve out the radio-AGNs.

The paper is organized as follows. Section 2 introduces the data used in this study. Section 3 presents the two alternative diagrams we propose to extract radio-AGNs. Section 4 discusses the connection between the classifications presented in this paper and other galaxy classifications. Section 5 summarizes our results.

2. Data

2.1. Radio Data

Our starting sample of radio-emitting galaxies consists of the 32,616 objects presented in the ROGUE I catalog. This catalog was made by selecting galaxies from the SDSS DR7 (see below) having a FIRST radio counterpart within 3″ from the optical position. It provides information about core and total radio flux density at 1.4 GHz, as well as on the morphology of the radio structure and of the optical host galaxy. There are 1537 galaxies clearly connected to extended radio sources, 940 galaxies connected with a possibly extended or one-sided structure, and 902 sources considered as SF, blended, or not related to a galaxy with an SDSS spectrum. As many as 29,237 objects fall into the unresolved or “elongated” (as opposed to “extended”; see Koziel-Wierzbowska et al. 2020) radio source categories.

The monochromatic radio luminosity at 1.4 GHz is calculated from the total radio flux density ($F_{1.4}$) as

$$L_{1.4} = \frac{4\pi D_L^2}{(1+z)^{1-\alpha}} F_{1.4},$$

where we take the spectral index to be $\alpha = 0.75$, which is close to the mean spectral index of sources detected at 1.4 GHz (e.g., Condon 1984; Smolčič et al. 2017), and the luminosity distance $D_L$ is calculated from the spectroscopic redshifts from SDSS. We assume a flat ΛCDM cosmology, with $\Omega_0 = 0.3$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2.2. Optical Data

Objects in the ROGUE I catalog have been selected from the SDSS seventh data release (DR7) database (Abazajian et al. 2009) and belong either to the Main Galaxy Sample (Strauss et al. 2002) or to the Luminous Red Galaxy sample (Eisenstein et al. 2001). Note that, in principle, these samples do not contain any Type I AGNs (although Oh et al. 2015 identified around 4000 galaxies with broad Hα lines in the full DR7 galaxy catalog).

The ROGUE I catalog contains only SDSS DR7 galaxies with redshift $z$ larger than 0.002 (which guarantees that luminosity distances are not dominated by peculiar motions; e.g., Ekholm et al. 2001) and S/N in the continuum at 4020 Å of at least 10, in order to allow a meaningful study of their stellar populations. Repeated spectra of the same galaxy were removed by matching galaxies in R.A. and decl. ($\Delta < 0.05$). From the ROGUE I catalog, we removed the small fraction of galaxies (0.2%) for which the Petrovsky half-light radius is negative or the stellar mass is smaller than $10^7 M_\odot$ in the STARLIGHT database, as well as the few objects that do appear in the published ROGUE I catalog but whose radio emission was found to be blended with another source or for which the optical galaxy is not the host of the radio emission (objects tagged B or ND in the catalog). Our final sample contains 32,163 galaxies and is referred to as the ROGUE I sample in the remainder of the paper.

The SDSS spectra allow us to derive certain physical quantities such as the redshifts, the total galaxy stellar masses ($M_*$), the black hole masses ($M_{BH}$), and $D_4(4000)$. These last quantities are obtained by means of the inverse spectral synthesis code STARLIGHT (Cid Fernandes et al. 2005) to fit the observed continuum emission of the galaxies. The black hole masses are derived from the stellar velocity dispersions ($\sigma_v$) using the relation by Tremaine et al. (2002), which is applicable for $\sigma_v \geq 70$ km s$^{-1}$, and $D_4(4000)$ is taken from the synthetic spectra as explained in Stasińska et al. (2006). Emission-line measurements were performed after subtraction of the synthesized stellar spectrum from the observed SDSS spectrum. All the data were obtained exactly as explained in Section 2 of Koziel-Wierzbowska et al. (2017) and can be retrieved from the STARLIGHT database9 (Cid Fernandes et al. 2009).

2.3. Mid-infrared Data

WISE observed the entire sky in four infrared bands with central wavelengths 3.4, 4.6, 12, and 22 μm (dubbed W1, W2, W3, and W4, respectively; Wright et al. 2010). The photometric sensitivity at $5\sigma$ is 0.068, 0.098, 0.86, and 5.4 mJy for each one of the four bands. The catalog contains positional data of more than 500 million objects with S/N > 5 for at least one of the bands. The photometric calibration was made in the Vega system, with conversion factors to the AB system of 2.699, 3.339, 5.174, and 6.620 for W1, W2, W3, and W4, respectively (Jarrett et al. 2011).

Emission in the W1 and W2 bands is more easily detected because of the sensitivity of the detector and because the data usually have better S/N. The widest band is W3, with a spectral coverage of 7–17 μm, which was designed to observe the strong polycyclic aromatic hydrocarbon (PAH) emission bands that are present in this range (Jarrett et al. 2011). The PAH emission is often associated with the presence of warm dust within molecular clouds, excited by the strong radiation field from the massive young stars immersed in it (da Cunha et al. 2008) and/or from the dust torus around an AGN (Alonso-Herrero et al. 2014). The main features of these kinds of emission are centered around 11 μm and hence detectable inside the W3 band for the whole redshift range probed by the ROGUE I sources ($z \leq 0.6$), while thermal emission is found within the W4 band, the most S/N-poor filter of WISE (Wright et al. 2010).

9 http://www.starlight.ufsc.br
We matched the WISE and the SDSS DR7 catalogs, identifying the most probable pairs within a 1\arcsec radius. To use the WISE measurements, we required S/N_{W3} \geq 2 to exclude spurious measurements and problems due to sensitivity. This is especially needed for early-type galaxies, which have little or no gas and are generally very faint in this spectral range.

Our final sample of galaxies with usable WISE data consists of 23,294 objects and will be referred to as the ROGUE I–WISE sample.

Throughout the text we also use the flux calculated for the W3 band. We obtain fluxes from Vega magnitudes using

\[ F_\nu [\text{Jy}] = F_\nu 10^{-0.4m_{\text{Vega}}}, \]

where \( F_\nu \) is the zero magnitude flux density and \( m_{\text{Vega}} \) is the WISE magnitude of the object. We use the zero-points and the relations from Jarrett et al. (2011)\(^{10}\) with a zero magnitude flux density \( F_\nu = 31.674 \) for W3 and assuming that the MIR spectral energy distributions do not significantly deviate from a power law \( (F_\nu \propto \nu^\beta) \).

3. Separating Radio-AGNs from Star-forming Galaxies

3.1. The Advantage of Using Only One Criterion

As mentioned in the introduction, we look for a unique criterion that would be able to separate SF galaxies from galaxies where the radio emission is linked to an AGN. The first problem with using several criteria together, as is the case of, e.g., Best & Heckman (2012), is that relevant data are not always available for all the objects, so that for some objects the classification has to rely on only a fraction of the chosen criteria.

We have matched their catalog of 18,268 objects to the STARLIGHT database and found 18,074 objects in common. To analyze their data, we used the radio fluxes from the Best & Heckman (2012) catalog and emission lines, stellar masses, and other spectral measurements from the STARLIGHT database. Objects that do not exhibit the four emission lines ([O III], H\(\beta\), [N II], and H\(\alpha\)) in the Baldwin et al. (1981, BPT) diagram cannot be classified using this criterion. This concerns 11,939 (66\%) of their entire sample of \( \sim 18,000 \) objects.

Second, for those objects with data allowing one to apply more than one criterion, classifications according to the various criteria do not necessarily agree. Let us consider the other two criteria used by Best & Heckman (2012), which are \( D_\alpha (4000) \) versus \( L_{1.4}/M_* \) and the relation between the H\(\alpha\) emission-line luminosity and the radio luminosity \( (L_{4.9}\alpha vs. L_{1.4}) \). Among the 9596 objects from Best & Heckman (2012) having all the required data to use the two methods, there are 1085 objects for which the classifications differ.

In the following subsections we present two methods that can be individually applied to radio catalogs depending on data availability.

3.2. The MIRAD Diagram

It has been known almost since the beginning of extragalactic radio astronomy and infrared astronomy (de Jong et al. 1985; Helou et al. 1985; Condon & Broderick 1988; Condon 1992, and references therein) and confirmed in recent studies (e.g., Wang et al. 2019) that there is a tight correlation between the radio luminosity and the far-infrared luminosity of “normal” SF galaxies, i.e., galaxies that do not contain an AGN. The radio emission in these sources consists of free–free radiation from HII regions and synchrotron radiation from supernova remnants (mostly Type II and Type Ib) whose progenitors are more massive than \( 8 M_\odot \), so it probes stellar populations younger than \( 5 \times 10^6 – 10^7 \) yr. The far-infrared radiation measures the bolometric luminosity of stars more massive than about \( 5 M_\odot \) processed by circumstellar dust.

Neither the radio emission nor the far-infrared emission is affected by dust extinction; thus, the observed radio flux and far-infrared flux are expected to be tightly linked. In the local universe (up to \( z = 0.15 \)), the relation is very tight, with a dispersion of about 0.25 dex (Yun et al. 2001). It has been used to identify jetted AGNs as objects deviating from this relation (Donley et al. 2005; Park et al. 2008; Del Moro et al. 2013). However, existing far-infrared data are from rather shallow surveys (IRAS, Neugebauer et al. 1984; or Infrared Space Observatory [ISO]) not deep enough to be useful for the characterization of ROGUE I galaxies, while Spitzer (Werner et al. 2004) data are available only for selected objects.

On the other hand, MIR surveys exist for the whole sky (AKARI, Murakami et al. 2007; WISE, Wright et al. 2010). Rosario et al. (2013) showed the luminosity in the W3 band versus \( L_{1.4} \) for a sample of emission-line AGNs selected from the SDSS galaxy database. They found that these emission-line AGNs were distributed into two branches. Seyfert galaxies gather on the upper branch, in the same region as a control sample of inactive SF galaxies. Low-ionization nuclear emission-line galaxies (LINERs) are split between the upper branch and the lower branch. These authors argued that, for the Seyfert galaxies, the W3 emission is almost entirely due to dust heated by ongoing star formation and highlighted the MIR–radio plane as a useful tool in studies of star formation and accretion properties of AGNs. The MIR–radio plane was also successfully used to study star formation properties of the radio/X-ray-selected sample by Mingo et al. (2016).

Figure 1 shows the ROGUE I–WISE sample on the log \( F_{W3} \) versus log \( F_{1.4} \) plane, which we dub MIRAD, as it is based on MIR and Radio fluxes. The full sample is plotted as gray error bars, which have been obtained by error propagation from the observed fluxes. Points in blue highlight the 2538 objects that are classified as pure SF galaxies according to Stasińska et al. (2006) on the [N II] \( \lambda 6584/H\alpha \) versus [O III] \( \lambda 5007/H\beta \) plane (requiring a minimum S/N of 3 in these emission lines). Several features are noteworthy. First, this plot shows two different families of objects, with SF galaxies falling on the upper sequence. Second, uncertainties are much smaller in \( F_{W3} \) than in \( F_{1.4} \) for the SF sequence, and the opposite is true for the lower sequence.

This diagram shows a very clear dichotomy among the population of galaxies with radio emission. We looked for objective criteria to draw a separation line. It turns out that an attempt to separate the BPT-pure SF galaxies and the Fanaroff–Riley type I (FR I) and type II (FR II) radio sources (Fanaroff & Riley 1974), in which radio emission is unambiguously connected to an AGN, gives an infinity of solutions that are equally valid. We thus chose the simplest of all, namely,

\[ F_{W3} = F_{1.4}. \]

where both quantities are in mJy. Surprisingly, as was shown by Rusinek et al. (2020), the same criterion separates

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\(^{10}\)And also from the WISE website, http://wise2.ipac.caltech.edu/docs/release/allsky/expsap/sec4_4h.html.
Figure 1. $\log F_{\text{w3}}$ vs. $\log F_{\text{1.4}}$ (i.e., the MIRAD diagram) for the objects in the ROGUE I–WISE sample (see text). The full sample is shown as gray crosses, whose sizes are the uncertainties in log fluxes. Points in blue are the 2549 pure SF galaxies as defined by Stasinska et al. (2006) on the [N II] λ6584/Hα vs. [O III] λ5007/Hβ plane. The 23,294 objects from the ROGUE I sample, together with the FR I and FR II radio sources. The solid line represents the limit below which the SF demarcation line is actually an upper envelope for ionization by massive stars. Possibly these objects do contain an active AGN. Detailed studies of them should provide more information about their nature.

Figure 2. $\log F_{\text{w3}}$ vs. $\log F_{\text{1.4}}$. The 23,294 objects from the ROGUE I–WISE sample are in gray. In blue we show the BPT-pure SF, and in red the FR I and FR II radio sources. The solid line represents the limit below which we consider that all the galaxies are radio-AGNs. Numbers in gray, red, and blue show how many of the ROGUE I–WISE, FR I and FR II, and BPT-pure SF objects fall above and below the dividing line, respectively.

Among the diagrams used by previous authors to select radio-AGNs, the DLM one is quite efficient and can be applied to objects with or without emission lines, whether or not they have any WISE detections. Different dividing lines have been proposed in the past (Best et al. 2005a; Kauffmann et al. 2008; Best & Heckman 2012; Sabater et al. 2019). Here, since we emphasized the utility of a unique diagram, and since we have shown that the MIRAD diagram works extremely well when no spectra are available and no redshift can be determined, we defined a line for the DLM diagram that is as compatible as possible with our dividing line in the MIRAD diagram. We proceeded as follows. For a given dividing line in the DLM diagram, we defined the completeness $C$ and the $R$ reliability fractions for the SF and AGN classes (Strateva et al. 2001). $C_{\text{SF}}$ is the fraction of galaxies classified as MIRAD-SF that are correctly classified as SF in the DLM diagram, whereas $R_{\text{SF}}$ is the fraction of galaxies classified as SF in the DLM diagram that are also MIRAD-SF. Defining $C_{\text{AGN}}$ and $R_{\text{AGN}}$ likewise for the radio-AGN class, we calculated the figure of merit $P$ (Baldry et al. 2004), which is the product of those four fractions: $P \equiv C_{\text{SF}}R_{\text{SF}}C_{\text{AGN}}R_{\text{AGN}}$. We calculated $P$ over a wide range of slopes and intercepts for the DLM dividing line, refining our search in the loci of the greatest values of $P$.

Two possible solutions were found:

$$D_a(4000) = -0.28 L_{1.4}/M_\star + 4.9$$

and

$$D_b(4000) = -0.23 L_{1.4}/M_\star + 4.3.$$
of radio-AGNs among radio sources. This needs to be remembered when dealing with demography of radio-AGNs. A way to circumvent this would be to use upper limits for the W3 detection in order to cull a sample of objects with low MIR emission.

4. MIRAD and DLM versus Other Classifications of Galaxies

4.1. Radio Classes

Figure 5 shows the distribution in the MIRAD diagram of the radio morphologies as listed in the ROGUE I catalog. As expected, almost all the extended radio morphologies (i.e., FR I; FR II; hybrid; bent sources that are wide-angle tail, narrow-angle tail, and head-tail; and restarted radio sources composed of double–double, X-shaped, and Z-shaped sources) are radio-AGNs. Unresolved and elongated radio sources, on the other hand, are found on both sides of the dividing line, in similar proportions. It is precisely for those cases that our diagrams are useful to pinpoint which objects correspond to radio-AGNs.

Figure 6 is the equivalent of Figure 5, but for the DLM diagram applied to the ROGUE I sample. Qualitatively, the results are similar to those obtained with the MIRAD diagram.

4.2. Black Hole Masses for Radio-AGNs

It has already been shown in many studies (e.g., Dunlop et al. 2003; Kozieł–Wierzbowska et al. 2017) that the fraction of radio-loud AGNs increases rapidly in galaxies with black holes more massive than $\log M_{\text{BH}}/M_\odot \sim 8$. Figure 7 shows the distribution of ROGUE I–WISE galaxies with black hole masses in different ranges in the MIRAD diagram, and Figure 8 shows the same for ROGUE I in the DLM diagram. A total of 1727 objects in the ROGUE I sample and 1707 objects in the ROGUE I–WISE sample have $\sigma_s < 70$ km s$^{-1}$, so they lack $M_{\text{BH}}$ estimates and are not included in any $M_{\text{BH}}$ bin.

We note that galaxies with low $M_{\text{BH}}$ fall preferentially above the MIRAD line and those with high $M_{\text{BH}}$ fall below it, suggesting that there is an optimal $M_{\text{BH}}$ separation between SF and radio-AGN. To find out which $M_{\text{BH}}$ value best corresponds to our MIRAD separation line, we again use the figure of merit $P$ (see Section 3.3), where the completeness $C$ and the $R$ reliability fractions are defined according to classification as SF or AGN by MIRAD and an $M_{\text{BH}}$ limit. Figure 9 shows $P$ as a function of the $M_{\text{BH}}$ threshold. For the MIRAD diagram and the ROGUE I–WISE sample (panel (a)), $P$ reaches its maximum value at $\log M_{\text{BH}}/M_\odot = 7.85$. For the DLM diagram applied to the ROGUE I sample (panel (b)), $P$ reaches its maximum value at $\log M_{\text{BH}}/M_\odot = 7.8$.

Thus, both the MIRAD and the DLM diagrams indicate that radio-AGNs are found almost exclusively among galaxies with black hole masses above $10^{7.8} M_\odot$.

4.3. Galaxy Morphological Classes

Figure 10 shows the distribution in the MIRAD diagram of the optical morphological classifications from the ROGUE I catalog. Spiral (S) and barred spiral (bS) galaxies are shown in blue; lenticular (L) and barred lenticular (bL) galaxies are shown in green; elliptical (E) and interacting elliptical (iE) galaxies are shown in red; galaxies with distorted morphology

extended radio-AGNs (out of a total of 999) in the SF zone, and only 27 BPT SF galaxies out of a total of 2568 (i.e., 1%) in the radio-AGN zone. So the DLM diagram with our dividing line seems to work even slightly better than the MIRAD diagram.

The total number of objects that can be classified with the DLM diagram is 32,163 (as opposed to 23,294 in the MIRAD diagram). However, the ratio of the number of radio-AGN to SF galaxies is 1.61 in the DLM diagram for the ROGUE I sample and 0.89 in the MIRAD diagram for the ROGUE I–WISE sample. In other words, many radio-AGNs are missing in the MIRAD diagram. Those are likely the ones that have too small flux in the W3 band to be detected. This means that the MIRAD diagram provides a biased estimate of the total number

Figure 3. $D_n(4000)$ vs. $L_{1.4}/M_*$ (DLM) diagram for the ROGUE I–WISE sample. Purple points: SF galaxies according to the MIRAD diagram; green points: radio-AGNs according to the MIRAD diagram. Thin lines: some previous dividing lines (dotted line: Kauffmann et al. 2008; dotted–dashed line: Sabater et al. 2019). Thick lines: dividing lines that minimize the difference with the MIRAD diagnostic (solid line: our first choice; Equation (5); dashed line: our second choice). In the following, all the diagnostics in the DLM diagram will be based on the solid line. The numbers indicate the total score of objects above and below the solid dividing line; the total is in gray, MIRAD-SF in purple, and MIRAD-AGN in green.

Figure 4. DLM diagram for the entire ROGUE I sample. Blue points: SF galaxies according to the BPT diagram. Red points: FR I and FR II radio sources.
Figure 5. Distribution of the objects with different radio morphologies in the MIRAD diagram. The ROGUE I–WISE sample is in gray. Sources with specific morphological types are marked in colors: unresolved sources in blue, elongated in green, FR I in red, FR II in magenta, hybrid in light yellow, bent sources (including wide-angle tail, narrow-angle tail, and head-tail radio sources) in dark yellow, and restarting sources (which are double–double, X-shaped, and Z-shaped sources) in brown.

Figure 6. Same as Figure 5, but for the DLM diagram and the ROGUE I sample.

Figure 7. MIRAD diagram in bins of BH mass. All the objects of the ROGUE I–WISE sample are represented as gray points. Superimposed in different colors are those objects having a BH mass within the limits indicated at the top of the panels.

Figure 8. Same as Figure 7, but for the DLM diagram and the ROGUE I sample.

(D), galaxies with mergers (M), interacting spiral galaxies (iS), and interacting lenticular galaxies (iL) are shown in light navy blue; and ring (R) galaxies are marked in purple.

Later-type galaxies (spirals and lenticulars) fall above the MIRAD separation line, whereas earlier-type ones (ellipticals) fall below the line. Galaxies showing signs of interaction also...
lie above the separation line, which suggests that their radio emission is connected to star formation. About 13% of interacting systems, however, are below the line, which is in agreement with the fact that a significant fraction of radio jets are found in mergers and interacting galaxies (see, e.g., Chiaberge et al. 2015).

Figure 11 is similar to Figure 10, but for the DLM criterion applied to the ROGUE I sample. Similarly to the MIRAD diagram, and even more conspicuously, it shows that the vast majority of radio-AGNs are found among elliptical galaxies.

4.4. Galaxy Spectral Classes

Figure 12 shows the distribution of the five categories of galaxies defined by Cid Fernandes et al. (2011) in the $W_{\text{H}\alpha}$ versus $[\text{N II}]/\text{H}\alpha$ diagram (the WHAN diagram):

1. Pure SF galaxies: $\log [\text{N II}]/\text{H}\alpha < -0.4$ and $W_{\text{H}\alpha} > 3$ Å, shown in blue.
2. Strong AGNs (i.e., Seyferts): $\log [\text{N II}]/\text{H}\alpha > -0.4$ and $W_{\text{H}\alpha} > 6$ Å, shown in dark green.
3. Weak AGNs: $\log [\text{N II}]/\text{H}\alpha > -0.4$ and $3$ Å $< W_{\text{H}\alpha} < 6$ Å, shown in light green.
4. Liny retired galaxies (RGs, i.e., fake AGN): $0.5$ Å $< W_{\text{H}\alpha} < 3$ Å, shown in orange.
5. Lineless RGs: $W_{\text{H}\alpha} < 0.5$ Å, shown in red.

Note that the value of $\log [\text{N II}]/\text{H}\alpha = -0.4$, which separates pure SF galaxies from AGNs in the WHAN classification of Cid Fernandes et al. (2011), is based on the line proposed by Stasińska et al. (2006) to separate pure SF galaxies from AGNs in the BPT diagram. Objects with $\log [\text{N II}]/\text{H}\alpha > -0.4$ may well experience present-day star formation, but the presence of an AGN can be detected in their optical spectrum (as compared to pure SF galaxies), be it at a level of a few percent. Figure 13 is the same as Figure 12, but for the DLM diagram applied to the ROGUE I sample.

A few objects in our samples (54 in the ROGUE I–WISE sample and 114 in the ROGUE I sample) cannot be classified with the criteria above: they have $W_{\text{H}\alpha} > 3$ Å (i.e., they are not retired) but lack an $[\text{N II}]/\text{H}\alpha$ measurement, meaning that they cannot be classified as being either an optical AGN host or an SF galaxy.

Figures 12 and 13 reveal that the SF and sAGN classes are distributed very similarly in the MIRAD and DLM diagrams. Only a small fraction of sAGNs are identified as radio-AGNs. The proportion is somewhat larger for wAGNs (which can broadly be identified with “true LINERS,” i.e., galaxies with low-level nuclear activity). In both the MIRAD and DLM diagrams, one can see that liny and lineless RGs constitute the vast majority of radio-AGNs: 79% in MIRAD and 87% for the DLM diagram. These percentages must not be taken literally, of course, but they show that any classification based on emission lines alone would miss the huge population of radio-AGNs that are lineless RGs.

AGN galaxies that have a radio counterpart are often divided into high- and low-excitation radio galaxies (HERGs and LERGs, respectively; e.g., Laing et al. 1994; Buttiglione et al. 2010). The “strong AGNs” in our radio-AGN sample can be roughly identified with HERGs, while “the weak AGNs,” as well as the liny and lineless RGs, would belong to the LERG class. It is to be noted that for the majority of the LERGs it is not possible to measure the bolometric luminosity of the AGN using optical emission lines. This obviously concerns the RGs, but even in weak AGNs the emission lines are strongly contaminated by emission due to ionization by hot low-mass evolved stars (HOLMES) and not by an AGN (see Cid Fernandes et al. 2011). In some radio galaxies shocks from radio jets may also play a role (e.g., Davies et al. 2017).

4.5. The Relation to Other Criteria to Identify Radio-AGNs

In addition to DLM, several other diagrams have been used in the past to help identify radio-AGNs in radio surveys. These are the BPT diagram, the $L_{\text{H}\alpha}$ versus $L_{\text{4\beta}}$ diagram (Best & Heckman 2012; Heckman & Best 2014), and the WISE color–color diagram used by Sabater et al. (2019). In Figure 14 we show these diagrams, color-coding the points according to their classification in the MIRAD diagram for the ROGUE I–WISE sample (panels (a)–(c)) and to the DLM diagram for the ROGUE I sample (panels (d)–(f)). For panels (a) and (d) we required $S/N > 2$ in all emission lines in the BPT, for panels (b) and (e) we required $S/N > 2$ for H$\alpha$, and for panels (c) and (f) we required $S/N > 2$ in all the WISE bands.

As obvious from the previous sections, classifications using emission lines will miss a large number of radio-AGNs. On the other hand, adding information from emission lines to the one obtained from the MIRAD or DLM diagrams will not improve the classification, since the latter two are clear-cut while both the BPT diagrams and the $L_{\text{H}\alpha}$ versus $L_{\text{4\beta}}$ diagram show a fuzzy separation between radio-AGNs and other objects, as seen in Figure 14. As has been shown by Stasińska et al. (2008, 2015), the BPT diagram, in addition to requiring good S/N in at least four emission lines, cannot distinguish galaxies with low-excitation active nuclei from RGs, i.e., galaxies that have stopped forming stars and are ionized by the HOLMES from their old stellar populations. The WISE color–color diagram was used by Sabater et al. (2019) to classify the sources according to a simple division at a given value of $W_2 - W_3$ first proposed by Herpich et al. (2016). Sabater et al. (2019) considered this diagnostic rather crude and used it mainly when their other diagnostics gave intermediate or contradictory classifications.

5. Summary

Considering the ROGUE I catalog, a sample of over 32,000 radio sources showing a radio core associated with optical galaxies, we have provided a simple way to separate radio-AGNs from galaxies where the radio emission is a result of recent star
formation. This technique will also be applicable to ROGUE II, the upcoming supplement to the ROGUE I, consisting of the SDSS radio galaxies without a close ($<3''$) FIRST detection. It can also be applied to other catalogs of radio sources, such as LoTSS.

While previous works (Best & Heckman 2012; Sabater et al. 2019) used a conjunction of criteria to sieve out radio-AGNs in catalogs of radio sources, we plead for the use of just one criterion. This provides a simpler diagnostic and a better evaluation of selection effects.

We propose two different diagnostic diagrams that are equally efficient and can be used on large samples of radio sources. One is $\log F_{\rm W3}$ versus $\log F_{1.4}$, dubbed the MIRAD diagram. This diagram only requires radio fluxes and photometry in the WISE W3 band with $S/N \geq 2$. It does not require any redshift determination. The MIRAD diagram neatly separates the radio sources in two branches. This was already found by Rosario et al. (2013) on a sample of optical AGNs and Mingo et al. (2016) on a sample of X-ray AGNs. Here we showed that the separation subsists when including purely SF galaxies and objects that cannot be optically classified as AGNs owing to the lack of emission lines, making it extremely useful to extract radio-AGNs from radio catalogs in which many sources are unresolved.

The other diagram is $D_n(4000)$ versus $L_{1.4}/M_\odot$, which we call the DLM diagram. This diagram has already been used in previous studies, but always in conjunction with other criteria. Here we argue that it does a perfectly good job when used alone.

For these two diagrams, we propose simple, empirical dividing lines that provide the same classification by both diagrams for the objects in common. These dividing lines classify correctly 99.5% of extended radio sources in the ROGUE I catalog into the radio-AGN class and 98%–99% of the BPT SF galaxies (using the
dividing line of Stasińska et al. (2006) into the SF class. In the ROGUE I catalog, the DLM diagram can be applied to a larger number of radio sources than the MIRAD diagram because it makes no use of MIR data. On the other hand, the DLM diagram requires optical spectra, which are not necessarily available for galaxies in radio catalogs (e.g., the LoTSS catalog). When it can be used, one must recall, however, that it may be affected by aperture effects. For example, in the case of observation of a nearby object (z \approx 0.05), the light collected by the SDSS fiber is dominated by the emission from a “retired bulge” (see Gomes et al. 2016; Herpich et al. 2016).

Both the MIRAD and the DLM diagrams clearly illustrate the well-known observational fact that radio-AGNs are preferentially found among galaxies with the most massive black holes. The distribution of the objects with different optical morphologies in the MIRAD and DLM diagram shows that most radio-AGNs correspond to elliptical galaxies.

About 90% of the radio sources classified in MIRAD or DLM diagrams as radio-AGNs are optically weak AGNs or RGs, i.e., galaxies that have stopped forming stars and are ionized by photons arising from their hot low-mass evolved stars. In the latter case, if the Hα line is detected, it is not related to the activity of the black hole.

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\textsuperscript{12} Any opinion, finding, and conclusion or recommendation expressed in this material is that of the authors, and the NRF does not accept any liability in this regard.

\textsuperscript{13} Astropy Python package: http://www.astropy.org.