Connecting MeerKAT Radio Continuum Properties to GAMA Optical Emission-line and WISE Mid-infrared Activity

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Abstract

The identification of active galactic nuclei (AGNs) in large surveys has been hampered by seemingly discordant classifications arising from differing diagnostic methods, usually tracing distinct processes specific to a particular wavelength regime. However, as shown in Yao et al., the combination of optical emission-line measurements and mid-infrared photometry can be used to optimize the discrimination capability between AGN and star formation activity. In this paper we test our new classification scheme by combining the existing GAMA-WISE data with high-quality MeerKAT radio continuum data covering 8 deg2 of the GAMA G23 region. Using this sample of 1841 galaxies (z < 0.25), we investigate the total infrared (derived from 12 μm) to radio luminosity ratio, q(TIR), and its relationship to optical–infrared AGN and star-forming (SF) classifications. We find that while q(TIR) is efficient at detecting AGN activity in massive galaxies generally appearing quiescent in the infrared, it becomes less reliable for cases where the emission from star formation in the host galaxy is dominant. However, we find that the q(TIR) can identify up to 70% more AGNs not discernible at optical and/or infrared wavelengths. The median q(TIR) of our SF sample is 2.57 ± 0.23, consistent with previous local universe estimates.

Unified Astronomy Thesaurus concepts: Radio active galactic nuclei (2134); Active galactic nuclei (16)

1. Introduction

Observations of galaxies at different wavelengths have shaped our understanding of their formation and evolution through time. However, the commonly derived parameters, such as stellar mass and star formation rate (SFR), rely on the assumption that the radiation received is exclusively generated by the stars within the galaxy. This assumption is true for pure star-forming (SF) galaxies, but not in the presence of an active galactic nucleus (AGN). AGNs are structures that radiate in the full electromagnetic spectrum, inducing additional flux to that emitted by stars. Although the most powerful (e.g., quasi-stellar objects) are easily identifiable, others with much weaker signatures can be hidden in the total emission from the host. AGNs with a non-negligible jet kinetic power are referred to as radio-loud (RLAGN) as opposed to the radio-quiet AGN (RQAGN) showing lower power (e.g., Peacock et al. 1986; Padovani 2011; Bonzini et al. 2013; Baloković et al. 2014). The RLAGNs can be classified as radiatively efficient (RE) or inefficient (RI) based on their jet power, accretion rate, and black hole mass, etc. BL Lac objects are RI objects in which the jets are oriented close to the line of sight of the observer, while the low excitation radio galaxies (LERG) are seen at an intermediate or large angle to the line of site. An RE system with a jet close to the line of site is classified as a core-dominated, flat spectrum, or optically violent variable quasar; at an intermediate and large angle, we have broad-line radio galaxies and narrow-line radio galaxies, respectively (see Table 1 in the review by Hardcastle & Croston 2020 for more details).

There are AGNs where the accretion disk is hidden either by the dust/gas in the torus or dust-obscured star-forming regions within the host galaxy (known as obscured AGNs) making it invisible to the observer depending on the wave band used. Extensive works over the years devised identification methods for obscured AGNs based on the following parameters: X-ray hardness, the nuclear extinction from spectral analysis, the

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width of permitted emission lines, etc. (see the review by Hickox & Alexander 2018).

The main source of radio emission in galaxies is synchrotron radiation, which is a nonthermal radiation caused by the acceleration of charged particles (mostly electrons) in the presence of a magnetic field. It is generated in SF regions by supernova remnants. The continuum radio emission is believed to be due to synchrotron emission by the relativistic electrons that rotate in the magnetic field carried by the jets in RLAGNs. The physical process that generates radio emission in RQAGNs is still not well understood. While some authors (Ulvestad et al. 2005) believe that synchrotron emission is due to less powerful jet in RQAGNs, others see shocks occurring in the accretion flow as the probable cause (see Ishibashi & Courvoisier 2011). The dynamics of accreting matter close to the central black hole likely induce dissipative processes in the accretion flow, and shocks are naturally generated in such environments (Blandford 1994; Courvoisier & Türler 2005; Ishibashi & Courvoisier 2009). Radio emission in RQAGNs is the main source of contamination that causes the departure from a linear far-IR/radio correlation (FIRRC).

Inside galaxies the optical and UV emissions from young and massive stars ($M > 8 M_\odot$) are absorbed by their surrounding dust and reemitted in the infrared. On the other hand, the synchrotron radiation occurs within the supernova remnants left by these same massive and short-life stars ($\sim$Myr versus Gyr for solar-mass stars) when they die (Voelk 1989; Lacki & Thompson 2010). This cycle is used to explain the tight FIRRC seen for SF galaxies (de Jong et al. 1985; Appleton et al. 2004; Ivison et al. 2010; Magnelli et al. 2010; Thomson et al. 2014). This strong relationship between the radio and infrared continuum has been very useful in many studies, such as estimating the SFR in dusty nuclear regions. The dynamics of accreting matter close to the central black hole likely induce dissipative processes in the accretion flow, and shocks are naturally generated in such environments (Blandford 1994; Courvoisier & Türler 2005; Ishibashi & Courvoisier 2009). Radio emission in RQAGNs is the main source of contamination that causes the departure from a linear far-IR/radio correlation (FIRRC).

However, all the AGN identification methods (see Padovani 2017), including the optical and infrared mentioned above, have a limited classification capability associated with the AGN’s signatures and attributes probed. For example, a separation between AGNs and SF galaxies becomes very difficult when the AGN’s host galaxy dominates the emission from the dusty torus (frequently the case for Seyfert-type galaxies). Similarly, optical lines become invisible when the AGN is completely obscured by dust, hence rendering the optical classification method ineffective. Studies have often found some X-ray AGNs among SF galaxies of the optical BPT classification (Trouille et al. 2011; Castelló-Mor et al. 2012; Pons et al. 2016; Agostino & Salim 2019).

Likewise, misclassifications are seen between optical BPT and infrared WISE color–color (Ching et al. 2017; Leahy et al. 2019; Yao et al. 2020). Huang et al. (2017), using 18-band SED fitting in the mid-infrared, recovered 20% more X-ray detected AGNs than using a mid-infrared color selection criteria. In contrast, Thorne et al. (2022) employ far-UV to far-IR SED fitting using Prospect, and find a significant AGN component in 91% of galaxies selected using narrow emission-line ratios and the presence of broad emission lines. They also find good agreement with mid-infrared color selections. On the other hand Hickox et al. (2009; see their Figure 8) found a relatively small overlap of about 30%–50% between the X-ray and IR-selected AGNs in the AGES sample at 0.25 < z < 0.8, and the radio AGNs are generally not selected in the other wave bands. Regarding all the preceding issues one can see that no single wave band can find all AGNs, but we rather need a multiwave band approach.

In our previous paper (Yao et al. 2020, here referred to as “Paper I”), we used robustly determined WISE photometry in combination with optical data from the Galaxy and Mass Assembly (GAMA, Driver et al. 2011) to create a new “hybrid” infrared–optical diagram—combinations of Hα, [N II] and WISE color—which greatly increases the number of galaxies classifiable using the conventional BPT diagram (by a factor of 4). With the advent of large radio surveys on ASKAP and MeerKAT, and soon the SKA itself, more studies will require quick and efficient ways to separate AGNs from SF populations without having to investigate the full energetic properties of these galaxies. We are revisiting the classification of AGNs across the electromagnetic spectrum with the latest radio, optical and infrared that we have available from the GAMA G23 field, to investigate how well these classification methods can be exploited to improve upon the field. Our aim is to present a classification scheme (Section 5), which shows the limitations as well as the power of combining these different wavelength regimes.

The structure of this paper is as follows: Section 2 describes the data used, including the radio continuum data reduction. In Section 3 we present the radio catalog, while the radio properties of different optical–infrared classes of galaxies (derived in Paper I) are investigated in Section 4. The discussion of our results is presented in Section 5. Finally, Section 6 summarizes our main findings.

The cosmology adopted throughout this paper is $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$. The conversions between the luminosity distance and the redshift use the analytic formalism of Wickramasinghe & Ukwatta (2010) for flat, dark energy-dominated universe,assuming standard cosmological values noted above. All magnitudes are in the Vega system (WISE photometric calibration described in Jarrett et al. 2011). Photometric colors are indicated using band names; e.g., W1–W2 is the [3.4 $\mu$m]–[4.6 $\mu$m] color. Finally, for all four bands,
the Vega magnitude-to-flux conversion factors are 309.68, 170.66, 29.05, and 7.871 Jy, respectively, for W1, W2, W3, and W4. Here we have adopted the W4 calibration from Brown et al. (2014b), in which the central wavelength is 22.8 μm and the magnitude-to-flux conversion factor is 7.871 Jy.

2. Data

2.1. Target Area

The MeerKAT Habitat of Galaxies Survey (MeerHOGS) was executed as part of the first MeerKAT call for proposals in early 2019 (Józsa et al. 2022, M. E. Cluver et al. 2022, in preparation). The observations covered a 10 deg² area targeting a nearby (z = 0.03) filamentary structure of galaxies within the GAMA (Driver et al. 2011) G23 field used for Paper I. It lies predominantly within the G23 region, except for a small portion at declinations < −35°. The MeerHOGS area to be cross-matched with G23 is therefore reduced to ~ 8 deg².

Figure 1 shows the survey’s L-band continuum footprint and final mosaic, while the upper-left, lower-left, and upper-right zoom insets are the galaxies IC5271, PKS 2250–351, and a ring-shaped galaxy that form part of our sample. These examples are taken from the resolved systems presented in Figure 4 (fluxes provided in Table 2), which will be discussed in Section 3.

Figure 1. The MeerHOGS survey pilot region located in the GAMA G23 region. The greyscale shows the continuum mosaic at 1.4 GHz, as observed by MeerKAT (64 dishes). The observations targeted a filamentary structure between 0.025 < z < 0.034 with a dense galaxy group at its center. The insets are close-up images of some well-resolved galaxies from our sample. Upper left: 3 × 3 arcmin image of disk galaxy IC5271, lower left is a 5 × 3 arcmin image of the giant radio galaxy PKS 2250–351 and upper right is a radio galaxy (3 × 3 arcmin image) which captured our attention owing to its circular-ring radio morphology. More resolved radio galaxies, including the ones highlighted in this figure are presented with details in Figures 4 and 16.

2.2. Optical and Mid-infrared Data

The primary data source used for this work is the optical and redshift data from the GAMA survey for the G23 region (Liske et al. 2015; Baldry et al. 2018), combined with infrared photometry from the WISE survey (Wright et al. 2010). This data is fully described in Paper I; however, we provide a brief overview here.

The optical line fluxes of the galaxies are extracted from the G23 GAMA II catalog (GaussFitSimplev05 from within the SpecLineSFR Data Management Unit; Gordon et al. 2017). The spectra are fitted with the IDL code mpfitfun (Markwardt 2009), which uses Levenberg–Marquardt nonlinear least squares minimization to identify the best-fitting parameters for the model, given the data and its associated uncertainties.

The mid-infrared photometry for the GAMA G23 region is constructed using the ALLWISE imaging frames, which have been reprocessed to enhance the spatial resolution. A customized pipeline is used to carefully characterize and extract the photometry of well-resolved galaxies, which is then combined with data from the ALLWISE catalog for the remainder of the sample (see Cluver et al. 2014; Yao et al. 2020 for details). To account for the redshifted emission across the optical and infrared bands, we applied a rest-wavelength correction (i.e., “k-correction”) to the magnitudes based on spectral energy distribution (SED) fitting before the derivation of any physical value.
The optical spectra of the GAMA galaxies for which the W1 magnitude $>15.5$ mag (0.2 mJy) were visually inspected looking for potential blending (mostly broad [Hα] line blended with [N II]) of emission lines in addition to taking into account the quality flag available, resulting in 9809 galaxies with high-quality photometry (the final sample or “study sample”). These galaxies should constitute one of the best-quality infrared–optical samples currently available. In this study we extend the power of this sample by combining it with the radio continuum data presented in Section 2.4.

2.3. The Optical–Infrared Classifications of Galaxies

In Paper I, we carried out an extensive study of both the optical (Baldwin et al. 1981) diagram (BPT) and the mid-IR WISE color–color diagram, which led to the creation of a new AGN-SF classification method. It has the advantage of combining the W1–W2 color and the optical [N II]/Hα line ratio, which proves to be a more efficient classification method than using WISE colors or optical line ratios alone. It allows the separation of galaxies into AGNs, pure SFRs, and a “mixed” class of composite galaxies believed to have AGN activity, but dominated by the star formation emission of the host galaxy (referred to as Mixed throughout this paper). A further classification is used for galaxies detected as AGN-dominated in the optical, but with significant star formation properties in the mid-IR: oAGN (msf); see Paper I. In contrast, the AGNs in this classification scheme (Figure 14(b) in Yao et al. 2020) are a combination of the optical and infrared classifications; similarly the SF sample is better defined owing to the fact that it reflects both the BPT and the WISE color classifications.

Earlier work using the WISE color–color diagram by Jarrett et al. (2011; see also Stern et al. 2012) derived color limits for AGN-dominated galaxies. These limits tend to be conservative as they were detecting mostly powerful infrared AGNs such as QSOs, obscured AGNs, and ULIRGs, yet missing the majority of low-power AGNs. The AGNs from this class will be referred to as the “Jarrett et al. (2011) classification.” Their properties will be compared to that of the AGNs in the new classification diagram, which has a much broader range of power. A summary table, which combines the different classification methods is presented in the discussion section.

2.4. Radio Continuum Data

2.4.1. Observations and Data Reduction

The MeerHOGS project is one of the first radio continuum surveys using MeerKAT. The total observation time was 16.5 hr (with 13.2 hr spent on the source) over $\sim$10 deg$^2$ at 1.4 GHz from the 2019 May 17–31, with 25 pointings in total (20 on the filament and an extra five in the dense galaxy group area). The total observation time for each pointing was $\sim$30 minutes. During each observation epoch, J2302-3718 was observed (2 minutes) for the purpose of gain calibration. PKS 1934-63 was also observed (three times 10 minutes) for bandpass and flux calibrations (see the observation details in Table 1). The available frequencies range from 900–1670 MHz, but only a reduced interval from 1319.8 to 1517.1 MHz (limited to redshifts $<0.1$) was used during the data reduction to minimize the data volume and mitigate the RFI contamination.

The data were reduced with the CARACal pipeline (Józsa et al. 2020). CARACal uses the Stimela Python framework, which can combine several versions of data reduction software in a system of containers (see Chapter 4 of Makhathini 2018 and references therein). The reduction process required 36 cores with a total memory of 300 GB.

AOFlagger (Offringa 2010) was run to flag for shadowing and RFI. PKS 1934-63 (primary calibrator) was first used for the bandpass and gain calibration. Then, the result was transferred to the second calibrator for combined gain and flux calibration. The calibration tables obtained were finally applied to the observation and the continuum imaging was done using WSClean (Offringa et al. 2014). During the imaging process, the source-finding software SoFiA (Serra et al. 2015) was used to generate a CLEAN mask using a threshold of $\sim$4$\sigma$ and following self-calibration with CUBICAL (Kenyon et al. 2018). The final image resulted in a synthesized beam of $13''$ $5 \times 13''$5 and an rms noise, $\sigma_{\text{rms}}$, that ranges from 11 to 16$\mu$Jy.

2.4.2. Source Extraction Using ProFound

The source finding and extraction was performed using ProFound (Robotham et al. 2018). A threshold of 3$\sigma$ resulted in approximately 18,000 sources (a source density of $\sim$1800 galaxies deg$^{-2}$). Our choice of ProFound was motivated by the fact that comparing ProFound to AEGEAN (Hancock et al. 2012, 2018) and pyBDSF (Mohan & Rafferty 2015). Hale et al. (2019) found that ProFound has the ability to capture the complicated shape of the galaxies best.

The distribution of the 1.4 GHz integrated flux densities for all the sources is shown in Figure 2. There is a rise in the number of detections starting from flux density $\sim$0.03 mJy to 0.08 mJy, reaching $\sim$5000 galaxies at the peak. It is followed by a constant (in the log) decrease in detections to a flux density of approximately 0.4 Jy. The average rms noise is 13$\mu$Jy, which means we are reaching 6$\sigma$ at 0.08$\mu$Jy and about 3$\sigma$ for the faintest sources.

In Figure 3 we compare the flux measurements from the MeerHOGS with that of the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) catalog data. The measurements from MeerHOGS are systematically brighter than that of the NVSS by 8%. A reduced sample of twelve galaxies, presented in Healy et al. (2021; Figure 2) using the fractional difference between MeerKAT and NVSS fluxes, shows a similar trend (except for the systematic offset in flux). However, they used an in-house NRAO software package called VSAD (see Section 5.2 of Condon et al. 1998) for their source extraction instead of ProFound. The scatter seen in our Figure 3 could be related to the difference in sensitivity between the two surveys. But, ProFound, whose model fit follows the distribution of the emission for each galaxy, is likely collecting slightly more flux as opposed to the extraction methods used for the NVSS, thereby contributing to the observed 8% systematic offset. It is also, however, likely that the MeerKAT flux calibration is a contributing factor. To ensure consistency with previous
Figure 2. Distribution of integrated 1.4 GHz flux densities of all sources. The number of sources peaks around a flux density \(\sim 0.1\, \text{mJy}\). The two galaxies at the brightest end (0.3–0.4 Jy) are respectively MH5 and MH19 shown in Figure 4 and Table 2.

Figure 3. MeerHOGS vs the ratio of MeerHOGS to NVSS flux density. The figure shows an 8% systematic. The MeerHOGS sources extracted using ProFound are on average \(\sim 8\%\) brighter than NVSS. This is likely related to the MeerHOGS calibration. Therefore, the median ratio of 0.92 was applied to correct the MeerHOGS 1.4 GHz flux densities. The total number of galaxies shown is 213.

studies, we apply a correction factor of 0.92 to bring our data in line with that of NVSS, allowing direct comparisons between our results and the findings of others.

3. The MeerKAT Radio Continuum Catalog

3.1. Resolved Sources

We extracted \(\sim 18,000\) radio sources from the MeerHOGS MeerKAT mosaic. The majority of detections are, however, point sources with relatively few \(\sim 170\) resolved galaxies (i.e., sources with dimensions at least twice the circular beam size of 13′/5). A selection of objects taken from the radio-resolved population is presented in Figure 4, with their fluxes given in

Table 2. This list of resolved objects is, however, based on visual inspection of the extracted apertures and continuum imaging; apart from the obvious cases of FRII sources such as MH2 or MH5 (see Figure 4), some of these may therefore be a chance superposition of sources and hence not necessarily physically associated.

FRII objects are luminous radio sources with hotspots in their lobes at the edge of the jets (see Fanaroff & Riley 1974). Sources with triple components like MH2, MH6, MH7, etc., are likely FRIs for which the central AGN is visible along with the lobes, as well as some complex systems with three radio components. FRII sources for which the central part is faint, or no longer visible, constitute the majority of the double components. Some exhibit one very bright lobe in comparison to the other; this is likely the result of an orientation effect boosting the jet pointing toward us at a low angle. This effect might be exacerbated when the angle is close to zero. Indeed, many single component sources and extremely bright galaxies in our radio catalog (about 50 cases; e.g., MH8 and MH9) seem not to have a counterpart in WISE, which means they are either emitting weakly in the IR or are distant galaxies whose directly pointing jets are being Doppler-boosted. They are intriguing galaxies that will need further attention with deeper spectroscopic data.

In addition we find some galaxies with abnormal morphology, such as MH3, which shows a bent shape probably caused by an interaction of the jet with its surrounding environment, or possibly a galaxy merger.

The largest angular source in our continuum imaging is MH4, identified as IC5271. It is a well-resolved \((118′\times 70′)\) disk galaxy in the radio and similarly in WISE (a WISE three-color image and other characteristics are presented in Appendix A, Figure 14). Such galaxies, resolved and large enough to do a pixel-by-pixel study, are rare, and MH4 is the only one in our entire sample.

It is followed by MH5, the famous PKS 2250–351, a radio giant galaxy for which flux measurements are available in several works (Brown & Burns 1991; Condon et al. 1998; Intema et al. 2009; and most recently, using ASKAP, Seymour et al. 2020). We found a total flux of \(\sim 293.112 \pm 0.6\, \text{mJy}\), which is similar to that found by the NVSS (285 \pm 29 mJy).

For resolved FRII galaxies like MH5, a visual inspection of the segmentation map is needed to sum the flux contributions from the lobes and the central galaxy to determine the total flux of the galaxy (see an example of the segmentation map in Figure 3 of Robotham et al. 2018). The jets of MH5 extend across \(\sim 350′\) (1.25 Mpc) from end to end. We reproduce for completeness several of the relevant measurements compiled by Seymour et al. (2020) in Table 3 and plotted in Figure 5. Consistent with steep-spectrum synchrotron emission, we see a rapid decrease (low to high frequency) of the flux in the two lobes, west (red) and east (blue), from \(\sim 200\, \text{mJy}\) at 675 MHz to \(\sim 10\, \text{mJy}\) at 9.5 GHz, while the emission from the core remains roughly constant (from 45 to 66 mJy). MH5 (PKS 2250–351) is also used as a comparative example of a powerful AGN in the analysis that follows.

3.2. MeerHOGS Cross-matched with the GAMA-WISE Sample

A cross-match of the radio data with the GAMA-WISE sample using a 5″ search radius resulted in 1841 radio galaxies having a WISE counterpart and a redshift available in GAMA (here referred to as the “MeerHOGS–GAMA–WISE sample”
Figure 4. A representative selection of resolved galaxies in the MeerHOGS region. Each MeerKAT radio continuum stamp is $5' \times 5'$ (except MH5, which is $7' \times 7'$) and the beam size is $13.5'$. See Table 2 for measurements. MH5 is a known giant radio galaxy (GRG), which will be discussed in the text. The contours are $20 \mu Jy$, $50 \mu Jy$, $150 \mu Jy$ and $300 \mu Jy$. The cyan crosses indicate the positions of the WISE galaxy catalog counterparts. See Figure 16 for additional sources.
We assess the reliability of our cross-match by making use of the method described in Ching et al. (2017; see Section 3.6), which is based on Monte Carlo simulations. The basic procedure is as follows: We first define the domain of possible events and generate them randomly. Then, we perform deterministic judgments of the system states based on the possible events and generate them randomly. Then, we perform the basic procedure is as follows: We

\[ R = \frac{1 - \langle N_{\text{rand}} \rangle}{\langle N_{\text{match}} \rangle} \]

where \( R \) is the current study reliability, \( \langle N_{\text{rand}} \rangle \) is the number of matches from the true catalog, and \( \langle N_{\text{match}} \rangle \) is the average number of matches using the random catalogs. Based on the preceding definition, we find 89% reliability using a 5″ cross-match radius between WISE and MeerHOGS positions. A 3″ cross-match radius leads to a higher reliability of 93.5% (for a 1″ it is 97.6%) but would result in the loss of ~30% of our current sample. Repeating the analysis in this paper with 3″ cross-match radius has a negligible impact on our analysis and leaves our findings unchanged. We additionally checked the possibility of having multiple WISE sources within 5″ of each MeerHOGS source. Only 45 cases (from a total of 1841 galaxies, ~2%) of multiple sources were found. Similarly only two cases (~0.1%) of multiple MeerHOGS sources were found within 5″ around the position of WISE sources. The positional offsets between MeerHOGS and WISE galaxies for 5″ cross-match radius are presented in the Appendix (Figure 17), showing excellent agreement.

In Paper I we devised a new classification scheme that identifies AGNs by combining optical excitation ([N II] and Hα) and the W1 – W2 color. The main criteria for this classification are [N II] and Hα lines in emission with S/N > 3, S/N (W1) > 5, and S/N (W2) > 5, respectively. 478 (478 from the total sample 1841 galaxies) galaxies from the MeerHOGS–GAMA–WISE sample satisfy these conditions.

The redshift distribution of the parent MeerHOGS–GAMA–WISE sample is presented in Figure 6. The total sample (black) is distributed with \( z \sim 0 \) up to \( z \sim 0.8 \), but no more than 2% of the galaxies are found beyond \( z = 0.5 \) (the nominal redshift limit of GAMA) and 76% have \( z < 0.3 \) (corresponding to the median redshift of the GAMA survey) that was used to derive the
the core remains of the steep spectrum, as suggested by Gopal-Krishna & Wiita postulate multiple shocks during the expansion of the jets as a potential cause shows a steep synchrotron signature. Given the large size of MH5, we can indicate this MeerHOGS data to distinguish it from NVSS. The EMU, where there is no measurement for the core. The larger point is used to three components of the galaxy are measured in all the surveys except for lobe, core, and West lobe respectively. 

combined classification scheme. The SF and Mixed galaxies using the (Yao et al. 2020) classification have a flat distribution between 0 ≤ z ≤ 0.3, but the AGNs appear to be more concentrated at z ~ 0.25, consistent with being rare and more readily detected in larger volumes (i.e., at greater distance). The AGNs classified by the method of Jarrett et al. (2011), which are generally very luminous in the mid-IR are found to z < 0.4. The star/galaxy separation algorithm used by the GAMA survey biases against QSOs, and they are hence rare in the GAMA catalog (e.g., Baldry et al. 2010).

4. Optical–IR–Radio Study of AGN vs SF

In this section, the MeerHOGS-GAMA–WISE sample is used to study the properties of AGNs and SF galaxies. Parameters such as stellar mass and SFR12 as stellar mass and SFR12 as a proxy for TIR—indicated here using (TIR). As shown by Cluver et al. (2017), the rest-frame luminosity from the W3 band closely tracks TIR luminosity, even in the presence of mid-infrared AGN, with a tight correlation (~15% scatter) between the two parameters given by Equation (1):

\[
\log_{10} L_{1.4 \text{GHz}}(L_\odot) = (0.889 \pm 0.018)\log_{10} L_{12\mu m}(L_\odot) + (2.21 \pm 0.15).
\] (1)

The 1.4 GHz radio flux densities were converted to rest-frame 1.4 GHz effective luminosities in Equation (2), assuming a radio spectral index of α = −0.7 (Ibar et al. 2010).

\[
L_{1.4 \text{GHz}} = 4\pi d_L^2 \frac{S_{1.4 \text{GHz}}}{(1 + z)^{\alpha}}.
\] (2)

The \(q_{\text{TIR}}\) ratio is defined in Equation (3) from Helou et al. (1985):

\[
q_{\text{TIR}} = \log_{10} g \left( \frac{L_{\text{TIR}}}{3.75 \times 10^{12} \text{ Hz}} \right) - \log_{10} g \left( \frac{L_{1.4 \text{GHz}}}{\text{W Hz}} \right).
\] (3)

An excess of \(q_{\text{TIR}}\) is an unambiguous signature of radio-loud AGNs, whereas radio-quiet AGNs follow the same radio–FIR Figure 6. The redshift distribution of the radio galaxies in MeerHOGS. The total Radio–Optical–IR sample is represented in black. We can see radio galaxies all the way to redshift z ∼ 0.6, but the bulk (>75%) of the distribution is at z < 0.3, which corresponds to the redshift limit applied to the GAMA-WISE study in Paper I. The distributions of the galaxies classified by our new classification diagnostic (Yao et al. 2020) are also presented, along with the AGNs classified using the WISE color method by Jarrett et al. (2011). All the classifications from Yao et al. (2020) are based on the GAMA-WISE sample limited to z < 0.3.
relation as SF galaxies. \( q_{\text{TIR}} \) is therefore an incomplete, albeit important, diagnostic.

In Figure 7 we show the W3 luminosity vs radio luminosity for the total sample. It includes all galaxy types, but a clear correlation between the two luminosities is evident. The high luminosities seen in the infrared and the radio for galaxies classified as AGNs (red and magenta) are probably dominated by the central AGN rather than being associated with evolving stars.

In Figure 8(a) we consider \( q_{\text{TIR}} \) versus the W1–W2 color, which acts as a mid-IR AGN discriminator (these delineations are from Yao et al. 2020). As already mentioned the W1 and W2 bands are sensitive to the continuum emission from evolved stars and the hot dust (only W2) making the W1–W2 color a good diagnostic for AGN emission (see, e.g., Jarrett et al. 2011; Stern et al. 2012). In panel (a) we show only the SF sample using the classification from Paper I (which is limited to \( 9 < \log_{10} \text{stellar/M}_\odot < 11 \); Section 5), which is by definition found in the IR SF zone.

For this SF sample, we calculate a mean value of \( q_{\text{TIR}} = 2.57 \pm 0.23 \) (black horizontal line). In a sample of 162 SF galaxies, Bell (2003) found a median \( q_{\text{TIR}} = 2.64 \pm 0.02 \) (red horizontal line), comparable to our result, albeit with less scatter. A similar result for \( q_{\text{TIR}} \) was found by Ocran et al. (2020) using data from the Giant Metrewave Radio Telescope (GMRT). They observed an evolution of the \( q_{\text{TIR}} \) with redshift in which the average \( q_{\text{TIR}} \) value at low redshift was \( \approx 2.8 \).

The black dashed line in Figure 8(a) is a 1\( \sigma \) cut (\( q_{\text{TIR}} = 2.31 \)) below the mean \( q_{\text{TIR}} \) of our distribution, which we consider to be a more robust SF sample since the radio and infrared emission are consistent, and will be used in Figures 10 and 11.

We simultaneously investigate the optical, infrared, and radio properties of our sample by observing the different AGN-SF categories in the \( q_{\text{TIR}} \) versus W1–W2 plane (see Figure 8(b)). All the types of galaxies appear to have comparable \( q_{\text{TIR}} \) values—even the AGNs selected using the selection by Jarrett et al. (2011) and the BLAGN from our sample have similar \( q_{\text{TIR}} \) compared to the galaxies classified as Mixed and SF. Several galaxies in the radio-bright regime are classified as either SFs or AGNs by the Paper I classification scheme (see blue and red points below \( q_{\text{TIR}} = 2.31 \) in Figure 8(b)). These represent galaxies whose IR emission is still significant enough to be classified as either SFs or AGNs in WISE, but with much stronger radio emission than what is expected from the radio–IR correlation (see Equation (3)).

Both M 87 and NGC 1316 are two well-known AGNs with massive stellar hosts (Jarrett et al. 2019) located in nearby galaxy clusters and not from our data set. They have radio fluxes of 138.487 Jy and 125 Jy (radio flux from the NVSS data, Condon et al. 1998), respectively. These radio fluxes are extremely high, but their SFRs (\( 138.487 \text{ Jy} \)) are from the NVSS data, Condon et al. 1998, respectively). These radio fluxes are extremely high, but their SFRs are comparable to our result, albeit with less scatter. A similar result for \( q_{\text{TIR}} \) was found by Ocran et al. (2020) using data from the Giant Metrewave Radio Telescope (GMRT). They observed an evolution of the \( q_{\text{TIR}} \) with redshift in which the average \( q_{\text{TIR}} \) value at low redshift was \( \approx 2.8 \).

The black dashed line in Figure 8(a) is a 1\( \sigma \) cut (\( q_{\text{TIR}} = 2.31 \)) below the mean \( q_{\text{TIR}} \) of our distribution, which we consider to be a more robust SF sample since the radio and infrared emission are consistent, and will be used in Figures 10 and 11.
4.2. The Variation of SFR $\mu$m and $q_{\text{TIR}}$ with Radio Power

We next explore the radio properties of our SF galaxies. As noted in Paper I, a mass constraint of $9 < \log_{10} M_{\text{stellar}} < 11$ has been applied to avoid the metallicity and color degeneracies that affect low-mass galaxies (Yao et al. 2020, see Section 3.4).

Beyond this mass regime, galaxies are moving off the star-forming main sequence of galaxies (see Cluver et al. 2020), likely connected to increased AGN activity.

With the addition of radio continuum data, we can now apply a further constraint to construct a more robust SF sample, achieved by applying the additional $q_{\text{TIR}} > 2.31$ cut. This

Figure 8. $q_{\text{TIR}}$ vs. W1–W2 colors. The W1–W2 color is widely used to separate AGNs from SF galaxies in infrared (see Assef et al. 2013) while the $q_{\text{TIR}}$ can discriminate between the radio SF and AGNs. The blue points represent the SF sample as defined in Section 2.3. The horizontal black and the dashed red lines are our mean value ($mean q_{\text{TIR}} = 2.57$) and that of Bell (2003; $q_{\text{TIR}} = 2.64 \pm 0.02$). The black dashed line is a 1σ cut ($q_{\text{TIR}} = 2.31$) below the mean $q_{\text{TIR}}$. The galaxies above this limit are our most robust SF sample, which will be used in Figures 10 and 11. All the galaxy samples, similar to Figure 7 are represented in (b). The crosses are the broad-line AGNs. The vertical-dotted lines are delimitations introduced by Yao et al. (2020). The SF galaxies are found at $W1-W2 < 0.5$ mag. The low-power IR AGNs have $0.5 < W1-W2 < 0.8$ mag and the powerful AGNs (QSOs, Obscured AGNs, etc.) have $W1-W2 > 0.8$ mag. Two well-known AGNs host galaxies (M87 and NGC 1316) are shown as examples for comparison. They have extremes (upper-limit) values given in brackets indicated by the red arrows. The black points in the background are galaxies of the MeerHOGS–GAMA–WISE sample, which do not respect all the criteria (constraints imposed on the S/N of the optical emission lines and WISE colors; see Section 3.2) to be classified using either the Yao et al. (2020) or Jarrett et al. (2011) method.

Figure 9. The same groups of galaxies from Figure 8 are represented in the $q_{\text{TIR}}$ vs. W2–W3 plane. The W2–W3 color mainly divides our sample of galaxies into quenched, stellar dominated for color magnitudes <2 mag, and dusty star-forming for higher (redder) magnitudes.

4.2. The Variation of SFR$\lambda_{12\mu m}$ and $q_{\text{TIR}}$ with Radio Power
SF galaxies with $q_{\text{LIR}} > 2.31$ in Figure 8). The relations of Brown et al. (2017), Davies et al. (2017), Murphy et al. (2011, radio), and Molnár et al. (2021) have been added. All the relations are converted to a Kroupa initial mass function (IMF), and the best fit of our data, given by the equation on the figure is slightly flatter than the others. The radio SFR by Murphy predicts the highest radio values. The blue triangle is the low-$\mu$SFR point in our sample and is also well resolved in IR. The radio and IR images of IC5271 are represented in Figures 4 and 14.

Our best fit is virtually identical to the fit of Davies et al. (2017). The difference in Murphy et al. (2011)’s much steeper relation is likely due to the fact their relation is derived using Hα data from diverse SF regions in a single galaxy, as opposed to global flux in a wider range of galaxies used in the other studies, including ours.

In Figure 11 we plot $q_{\text{TIR}}$ as a function of radio luminosity, color-coded by the redshift, to investigate the relative variation of the two parameters from low-$z$ to 0.3, the imposed cut-off. We find a decreasing trend in $q_{\text{TIR}}$ with increasing radio luminosity for galaxies located at higher redshift. The trend is unlikely to be an evolutionary effect, instead reflecting a Malmquist bias in the sample, which is incomplete to SF galaxies at higher redshifts. This trend is given by:

$$q_{\text{TIR}} = (-0.25 \pm 0.02) \log_{10} L_{\text{1.4GHz}} + (17.02 \pm 0.38)$$

(4)

for our sample of low $z$ (<0.3) galaxies. We note that this is also reported in Molnár et al. (2021), although their relation is offset to lower $q$ value by 0.21.

It is important to mention that the 10%–15% scatter observed in the $q$ value (see Figures 8–11) is a combination of intrinsic (physical) differences and photometric uncertainties, but also scatter that is induced by the rest-frame correction itself, in both the radio and infrared fluxes. In the radio, the adopted spectral index is a mean value for star-forming galaxies, but will certainly vary from one galaxy to the next. In the infrared, the k-correction is more complex, taking into account spectral features that redshift into the bandpass. In Appendix B, we discuss the method used to correct the WISE fluxes to the rest-frame, and consider the expected uncertainties that is contributing to the scatter observed in the $q$ ratio. For the redshift range of this study, the expected uncertainty in the rest-frame W3 flux and hence luminosity is 5%–10% (and lower still for redshifts <0.1; see Figure 19 in Appendix B).

### 4.3. The Relationship between $q_{\text{TIR}}$, WISE Color, and Stellar Mass

In Figure 12 the $q_{\text{TIR}}$ ratio is shown vs the W1–W2 color and is color-coded by stellar mass. While Figures 8(b) and 9(b) use the radio galaxies only classifiable by the classification method in Paper I (478 galaxies), Figures 12 and 13 present all galaxies in the MeerHOGS-WISE-GAMA sample, which can be classified according to WISE (1437 from the total sample 1841 galaxies).

The galaxies with high stellar masses commonly have a low W1–W2 color because they are old, quenched, and stellar dominated; the radio-bright population lies largely in this

![Figure 11. The radio luminosity as a function of $q_{\text{TIR}}$, color-coded by the redshift ($z$), for SF galaxies with $9 < \log_{10} M_{\text{stellar}} < 11$ and $q_{\text{TIR}} > 2.31$ (the mean $q_{\text{TIR}}$ of this sample is 2.69 ± 0.2). We used the IR radio luminosity relation as defined by Helou et al. (1985). In this relation, the total IR luminosity ($L_{\text{TIR}}$) is derived using the equation from Cluver et al. (2017) that relates $L_{\text{W1}}(12\,\mu\text{m})$ to $L_{\text{TIR}}$. The relation derived by Molnár et al. (2021) is added for comparison. Our best fit is represented by the black line (see the equation in the figure). The overall trend with redshift is likely the result of a distance–luminosity bias in the sample. The blue triangle is Galaxy IC 5271, which has the largest radio disk in our sample. It is an active SF galaxy with $SFR_{12\mu\text{m}} \sim 1.7 \, M_{\odot} \, \text{yr}^{-1}$.](image-url)
category. Some high-mass galaxies can be found in the IR AGN region (high W1–W2 color).

The GRG (MH5), classified as an AGN in the literature (Seymour et al. 2020), is in the WISE mid-IR “warm” zone of the color–color diagram (see Figure 15 for more detail about MH5) and is also powered by its central engine. We note that the infrared emission is dominated by the AGN and as such the log$_{10}$ $M_{\text{stellar}}$ is likely slightly overestimated due to hot dust contaminating the W1 emission. This source is a good example of those radio-bright AGNs for which the IR emission is strong, but the radio luminosity is very high, hence the low $q_{\text{TIR}}$: such that both the WISE color–color diagram and the $q_{\text{TIR}}$ classify them as AGNs. Details about the GRG are available in Table 3 and Figure 4.

We therefore consider the WISE color–color diagram, color-coded by $q_{\text{TIR}}$ and stellar mass, respectively, in panels (a) and (b) of Figure 13. The stellar-dominated region is where massive ellipticals are believed to have exhausted their reservoirs of cold gas, and are seen as inactive giant galaxies. The $q_{\text{TIR}}$ ratio (Figure 13(a)) reveals a different picture in which, although the galaxies appear quiescent in the IR (old star-dominated colors), they are far more active in radio emission. The radio emission is likely coming exclusively from the central SMBH. M87 is a prototypical example, and was the target of the first-ever image captured of a black hole (Event Horizon Telescope Collaboration et al. 2019).

The massive and radio-bright (radio-loud or luminous, see Figure 13(b)) galaxies located at low W2–W3 (<2 mag), i.e., with very low or imperceptible star formation activity (SFR < 1) in WISE are a category of AGNs that can only be identified using a combination of radio and IR emission (they generally show absorption lines in optical spectra).

Conversely, the galaxies in the WISE warm zone, like that of the QSOs and obscured AGNs, show the same $q_{\text{TIR}}$ range (2 < $q_{\text{TIR}}$ < 3.4, see Figure 9(b)) as the normal SF galaxies. This shows that WISE is more efficient in detecting the thermal change (hot and warm dust) in a galaxy with characteristics of AGN activity.

5. Discussion

Our observations at ∼1.4 GHz using the full MeerKAT array found ∼18,000 radio sources in a total area of ∼10 deg$^2$ down to a flux density limit of 0.2 mJy. This represents a source density of ∼1800 galaxies deg$^{-2}$. A sample of 1841 galaxies forms the combined multiwavelength sample consisting of radio galaxies having WISE and GAMA optical counterparts with W1 < 15.5 mag (195 μJy).

We carried out the determination of the $q_{\text{TIR}}$ ratio for the SF galaxies at redshift $z < 0.25$, which yielded a range from 2 to 3.4 with a mean value of 2.57 ± 0.23, similar to 2.64 ± 0.02 found by Bell (2003). However, there is a clear bias toward lower $q_{\text{TIR}}$ values at higher $z$ (see Figure 11). The range of $q_{\text{TIR}}$ from 2.10 to 3.11 in Bressan et al. (2002) using 26 compact ULIRGs is also in good agreement with our findings.

The galaxies classified as AGNs (e.g., see classification presented in Figure 9(b)) in our sample are not noticeably different from the SF galaxies in terms of the $q_{\text{TIR}}$ values. The AGN in these galaxies is definitely affecting the estimation of both luminosities (radio and IR) such that the $q_{\text{TIR}}$ is still deceptively consistent with that of SF galaxies. AGNs will typically be found at $q_{\text{TIR}} < 2$ (Baam & Klöckner 2006) when the galaxy is no longer forming stars.

Both types of AGNs (red and magenta; Yao et al. 2020 and Jarrett et al. 2011) share similar $q_{\text{TIR}}$ values to the SF galaxies (blue) as presented in Figure 8(b). However, their W1–W2 colors indicate a hot dust component, likely associated with AGN accretion, which confirms AGN activity that clearly separates them from pure SF galaxies in this diagram. Hence, in this case, the radio luminosity and the W1–W2 color reveal the presence of AGN activity.

In our recent study, which combined carefully measured WISE photometry and optical data (Yao et al. 2020), we found several galaxies with optical lines characteristic of AGNs, but with low W1–W2 mag values, indicative of normal star-forming processes. These have been classified as “optical AGNs (WISE SF)” and are particularly interesting to examine in the radio. Nine of these galaxies (GAMA ID: 5154519, 5155115, 5222053, 5234844, 5237886, 5240322, 5240366, 5258350, and 5427366) have radio counterparts in MeerHOGS. They do not show clear excess in radio and have $q_{\text{TIR}}$ values ranging between 2 and 2.8 with a mean of 2.38. The host likely dominates the IR and radio emission (see 5155115 in Figure 25 from Paper I) in which case luminosities in both wavelength regimes are similarly affected. It could also signify that the optical lines in these galaxies, although mimicking AGN activity, are not (partially or fully) induced by a central AGN. They exhibit high log L[OIII] (>41.2 erg/s) and 10.1 < Log($M_{\text{stellar}}/M_\odot$) < 11.0 with a mean of 10.61. In the current study, the $q_{\text{TIR}}$, like the infrared, does not indicate AGN activity in these galaxies. It seems to confirm the hypothesis that their accretion disk is not powerful enough to generate the winds that produce broad-line regions or, alternatively, that the [OIII] lines are coming from non-nuclear shocks rather than from the central AGN (see Yao et al. 2020 for further discussion).
On the other hand, radio excess was observed in some WISE galaxies, mainly among the stellar-dominated, quenched population. The IR–X-ray study by Huang et al. (2017) showed that building SEDs with data collected at several different frequency bands (combining WISE, Spitzer, and AKARI that provide continuous IR coverage from 2 to 24 μm) helps reveal an important fraction of hidden AGNs in SF galaxy samples. Indeed, the four WISE bands are robust enough to identify AGNs, but are limited in cases where the accretion energy of the AGN (low-power AGNs) is submerged by the star formation activity and the underlying stellar population of the host. Including an AGN model in the SED fits (e.g., ProSpect; Robotham et al. 2021) appears to be a viable method, which can then reliably identify these low-power AGNs, with the advantage of recovering AGN luminosities (see Thorne et al. 2022). Another issue in this regard is whether there is enough dusty material around the AGN to be clearly detected and delineated in the IR.

Figure 13. The WISE color–color diagram coded by the $q_{\text{TIR}}$ and the stellar mass in (a) and (b), respectively. Zone 1, 2, and 3 in (a) are the respective locations of the WISE powerful AGN (Jarrett et al. 2011 classification), the low-power AGN and finally, the non-AGN zone mostly populated by star-forming and quenched galaxies (see Figure 9 in Yao et al. 2020; here the spheroids are included in region 3). We can see the galaxies with the lowest $q_{\text{TIR}}$ in the quenched and stellar-dominated zone. It is quite interesting to see how the galaxies in this area of the WISE color–color diagram appear to be very prominent in radio. Since star formation is mostly associated with dust, not having a dust signature (very low SFR) in WISE means that the radio flux is probably coming exclusively from the central AGN (local examples are M87 and NGC 1316). This comes as a complementary finding in our quest to identify all forms of AGN through multiwavelength study. GRGC represents the core (41.4 mJy) of the giant radio galaxy (PKS 2250–351) from our sample (MH5). The blue and green dashed sequences’ relations were first introduced in Figure 9 from Yao et al. (2020). The galaxies between the green dashed line and the AGN box are classified as WISE warm galaxies and are believed to be low-power AGNs (Yao et al. 2020). However, their $q_{\text{TIR}}$ looks similar to that of normal SF galaxies. The black circles are galaxies classified as AGN in the optical BPT, but SF in infrared colors (see legend of Figure 8(b)).
cases are frequent among AGNs with a “hot” accretion mode (see review by Fabian 2012) known as low excitation radio galaxies (LERGs), which emit almost exclusively in the form of powerful radio jets. They are seen in our IR radio analysis as galaxies having $q_{\text{TIR}} < 2.31$ combined with low SFR$_{12\mu m}$.

Several studies in the literature (Magnelli et al. 2015; Calistro Rivera et al. 2017; Delhaize et al. 2017; Ocran et al. 2020) have shown a variation of the $q_{\text{TIR}}$ with redshift. Although our study does not focus on the evolution of the FIR/radio luminosity with redshift, we do see a decrease of the $q_{\text{TIR}}$ with the radio luminosity (see Figure 11) similar to the result found in Molnár et al. (2021). We place our $q_{\text{TIR}}$ values in context in Figure 11—this confirms that the decrease we observe is related to redshift. Indeed, as expected, the radio luminosities increase with redshift as would be the case for a luminosity selection effect. At relatively low redshifts, $z < 0.15$, we find $q_{\text{TIR}}$ with a value above 2.5, in agreement with that of Bell (2003) and Molnár et al. (2021).

In the WISE color–color diagram (Figure 13) the green curve represents the limit between the pure SF systems (with a few exceptions) and galaxies which we believe have some degree of AGN activity. Above this line are the infrared “warm” galaxies (from Paper I), which could be a mixture of AGN and SF activity. At larger W1–W2 color (W1–W2 > 0.8 mag) lie galaxies with stronger AGN activity in the infrared, which are mainly quasars, broad-line, and obscured AGNs. But, most of the galaxies in these AGN-dominated regions of the color–color diagram (see Figure 13(a)) have high values of $q_{\text{TIR}}$ similar to that of SF galaxies. The $q_{\text{TIR}}$ is failing to identify most of the AGNs in this region. We think the limitations of the $q_{\text{TIR}}$ is related to the fact that the hot accretion from the AGN is creating mid-infrared emission that mimics star formation (see Cluver et al. 2017; Jarrett et al. 2017).

Finally, we present Table 4 as a summary of the classification methods used in Paper I (see Section 2.3), extended in this paper to include $q_{\text{TIR}}$. This serves to show the power (and limitations) when combining optical, mid-infrared and radio diagnostics to efficiently separate AGN- and SF-dominated galaxies. This is therefore a summary of the results of both Paper I and the current paper.

| Jarrett et al. (2011) Class | Yao et al. (2020) Class | $q_{\text{TIR}}$ Class | Final Class | Examples |
|-----------------------------|------------------------|------------------------|--------------|----------|
| AGN?                        | AGN?                   | AGN?                   | AGN?         | See galaxies in Figure 13(a) |
| Case 1                      | yes                    | yes                    | yes          | Low $q_{\text{TIR}}$ (<2.3) in region 1 |
| Case 2                      | yes                    | yes                    | no           | High $q_{\text{TIR}}$ (>2.3) in region 1 |
| Case 3                      | no                     | yes                    | yes          | Low $q_{\text{TIR}}$, in region 2 |
| Case 4                      | no                     | yes                    | no           | High $q_{\text{TIR}}$, in region 2 |
| Case 5                      | no                     | no                     | yes          | Low $q_{\text{TIR}}$, in region 3 |
| SF or Mixed?                | SF or Mixed?           | SF or Mixed?           | SF or Mixed? | See galaxies in Figure 13(a) |
| Case 6                      | yes                    | yes                    | yes          | High $q_{\text{TIR}}$, in region 3 |
| Case 7                      | yes                    | no                     | no           | Low $q_{\text{TIR}}$, in region 2 |
| Case 8                      | yes                    | yes                    | no           | Low $q_{\text{TIR}}$, in region 3 |
| Case 9                      | yes                    | no                     | yes          | High $q_{\text{TIR}}$, in region 2 |
| Case 10                     | no                     | no                     | yes          | Low $q_{\text{TIR}}$, in region 1 |

Note. The AGNs identified using the high W1–W2 color cut (>0.8 mag) by Jarrett et al. (2011; JC) are also included in the classification of Yao et al. (2020; YC), except those for which the optical lines are in absorption. On the other hand, the YC can identify the low-power AGN not taken into account by JC. A significant proportion of the AGNs using the $q_{\text{TIR}}$ is not seen by JC and YC. However, the $q_{\text{TIR}}$ is not very efficient in the identification of low-power AGNs. It is unlikely for a galaxy to be classified as AGN in JC and not in YC.

We recall that the Yao et al. (2020) classification takes into account both the optical and infrared properties of the galaxies. In general, a galaxy is likely to have AGN activity when at least one of the methods can detect it. It follows that a galaxy has to be classified as an SF system in all three methods to be accepted as such.

For example, case 5 or 8 in Table 4 is a scenario where both the Jarrett et al. (2011) and Yao et al. (2020) classifications, respectively referred to as JC and YC, do not indicate any AGN activity, but the radio power is able to classify a source as an AGN based on the $q_{\text{TIR}}$. Such galaxies radiate the bulk of their flux at radio wavelengths and generally have weak emission in the infrared and/or the optical lines are in absorption. They are, therefore, classified as AGNs, or radio galaxies. Case 5 (or 8) represents a galaxy in region 3 of Figure 13(a), with a low $q_{\text{TIR}}$ value ($q_{\text{TIR}} < 2.31$, characteristic of radio AGNs). Case 9 or 4 is an SF in JC and AGN in YC (it is therefore a weak AGN located in region 2 of Figure 13(a)) with a high $q_{\text{TIR}}$ ($q_{\text{TIR}} > 2.31$) characteristic of radio SF galaxies. Case 10 is similar to 2, where only the $q_{\text{TIR}}$, does not detect the AGN activity. We think such AGNs have very low emissions in radio. On the other hand, cases 3 or 7 represent a low-power AGN in infrared (according to the Yao et al. 2020 classification), and not detected using the classical AGN classification method (Jarrett et al. 2011), but its presence is confirmed by the low $q_{\text{TIR}}$ ratio. Cases 1 and 6 show no ambiguity since all methods agree on the classification.

In this study, we consider the combination of optical spectroscopy, infrared, and radio imaging to more reliably identify and separate star-forming and AGN-dominated galaxies, and combinations of the two phases. In this emerging era of large radio surveys such as MeerKAT and ASKAP and soon the SKA itself, it is vital that we have empirical tools for classifying galaxies by their dominant emission mechanisms, which belie their evolutionary stage and path forward. There is no perfect way of doing this classification, there will always be uncertainties and overlap between different populations. As with the extensive previous work in this field since the days of IRAS when the infrared window provided a new view into the galaxy evolutionary process, it is our aim to mitigate systematic misclassifications (reliability) and improve upon the sample.
6. Conclusions

We processed the radio continuum data obtained with MeerKAT (64 dishes) at 1.4 GHz for a total area of ∼10 deg² in the southern region of GAMA (G23), known as the MeerHOGS survey. Although the observation time was only 16.5 hr, we obtained excellent image quality down to 20 μJy because of the exceptional sensitivity of MeerKAT. We found several notable multicomponent objects, as presented in Figures 4 and 16. The radio sources were extracted and position cross-matched to WISE galaxies with GAMA redshift in Table 4 attempts to bring some clarity to this critical step.

1. The q_{TIR} decreases with $L_{1.4\,\text{GHz}}$ for SF galaxies and its values range from 2 to 3.4 with a median value in the local universe ($z < 0.25$) of 2.57 ± 0.23. We relate this decrease to the Malmquist bias rather than a physical phenomenon.

2. We found a tight correlation between the SFR_{12} and the $L_{1.4\,\text{GHz}}$ for SF galaxies given by: 

$$\log_{10} \text{SFR}_{12} = (0.8 ± 0.02) \log_{10} L_{1.4\,\text{GHz}} - (17.02 ± 0.38)$$

and consistent with previous studies.

3. The galaxies identified as stellar dominated (quenched) in the WISE color–color diagram generally have low SFR and $q_{TIR}$ values < 2.51. These galaxies, considered to be inactive in the IR are powerful AGNs that probably emit most of their power at radio wavelengths. In this work, we identify them as “radio bright.”

4. The $q_{TIR}$ robustly identifies AGNs where the radio emission dominates because the host galaxy star formation is generally quenched. It becomes less reliable for cases where the galaxy, although showing clear signatures of AGN activity, still has active star formation. These AGNs in most cases share a similar $q_{TIR}$ range compared to that of robustly identified star-forming galaxies.

5. The BPT and WISE color–color diagrams are unable to accurately classify these radio-bright galaxies due to their lack of distinctive AGN emission at optical and infrared wavelengths. On the other hand, the $q_{TIR}$ is limited to radio-bright galaxies. We therefore suggest the combination of the three methods is best for classifying AGNs and SF galaxies. The combination of the $q_{TIR}$ and the WISE color–color (or the optical BPT) diagram is therefore quite powerful. See Table 4 for a summary of the classifications addressed in this work.

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GAMA is a joint European-Australasian project based around a spectroscopic campaign using the Anglo-Australian Telescope. The GAMA input catalog is based on data taken from the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. Complementary imaging of the GAMA regions is being obtained by a number of independent survey programs including GALEX MIS, VST KIDS, VISTA VIKING, WISE, Herschel- ATLAS, GMRT, and ASKAP, providing UV to radio coverage. GAMA is funded by the STFC (UK), the ARC (Australia), the AAO, and the participating institutions. Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under program ID 177.A-3016. The GAMA website is http://www.gama-survey.org/.

**Software:** CARACal (Józsa et al. 2020), AOFlagger (Offringa 2010), ProFound (Robotham et al. 2018), Stimela (Makhathini 2018), WCSIclean (Offringa et al. 2014), CUBICAL (Kenyon et al. 2018), SoFiA (Serra et al. 2015), VSAD (Condon et al. 1998), AEGEAN (Hancock et al. 2012, 2018), pYBDFS (Mohan Mohan & Rafferty 2015), mpfitfun (Markwardt 2009).

**Appendix A**

**Resolved Galaxies**

Figures 14 and 15 represent galaxies MH4 and MH5, respectively from Figure 4. They are also used as case examples throughout the document. The WISE three-color image and the color–color along with the main sequence diagrams are presented. The pinwheel (Jarrett et al. 2019) gives a good summary of all the properties such as colors, stellar mass or SFR, etc.

Figure 16 presents more resolved galaxies from our radio sample in addition to Figure 4. Their radio fluxes are in Table 5.

Figure 17 shows the difference between MeerHOGS and WISE pointing. The offset are minimal with average values of 0.1268 and 0.0202 arcsec along RA and DEC, respectively.
Figure 14. Physical properties of the galaxies selected as well-known cases. Here we show the infrared properties of IC 5271, which include the colors and physical properties. The lower right panel shows a pinwheel diagram, which displays the physical properties of the galaxies (see Jarrett et al. 2019 for more details about the diagram). IC5271 (MH4) is classified as SF in WISE with a radio flux of 0.0227 Jy.
Figure 15. The radio image presented in Figure 4, MH5 is a giant radio galaxy (PKS 2250–351 in A3936, Seymour et al. 2020) classified as SF in WISE with a MeerKAT radio flux of 0.318 Jy.
Figure 16. List of additional resolved galaxies similar to Figure 4. Each stamp is $5' \times 5'$ and the beam size is $13''5$. See Table 5 for measurements. The contours are $20 \mu Jy$, $50 \mu Jy$, $150 \mu Jy$ and $300 \mu Jy$. The cyan crosses represent the positions of the WISE's galaxy catalog counterparts where detected.
### Table 5

| Galaxy id | R.A. (deg) | Decl. (deg) | N. Comp. | East Comp. (mJy) | Central. Comp. (mJy) | West Comp. (mJy) | Total Flux (mJy) |
|-----------|------------|-------------|----------|------------------|----------------------|-----------------|----------------|
| MH21      | 345.5588   | −32.1676    | 2        | 0.4              | N/A                  | 0.06            | 0.46           |
| MH22      | 345.84269  | −32.8988    | 2        | 14.03            | N/A                  | 15.85           | 29.88          |
| MH23      | 345.0538   | −33.0967    | 2        | 2.67             | N/A                  | 6.69            | 9.35           |
| MH24      | 344.232    | −33.37644   | 2        | N/A              | 10.62                | N/A             | 10.62          |
| MH25      | 343.06187  | −33.9268    | 2        | 3.72             | N/A                  | 7.1             | 10.82          |
| MH26      | 343.21430  | −34.3146    | 2        | 5.12             | N/A                  | 12.1            | 17.21          |
| MH27      | 342.74987  | −34.36203   | 2        | 4.01             | N/A                  | 3.06            | 7.07           |
| MH28      | 344.07075  | −34.76574   | 2        | 5.54             | N/A                  | 6.02            | 11.56          |
| MH29      | 341.3357   | −34.77133   | 3        | N/A              | 3.46                 | N/A             | 3.46           |
| MH30      | 342.6264   | −35.2621    | 2        | 8.9              | N/A                  | 5.92            | 14.81          |
| MH31      | 341.13076  | −35.21164   | 3        | 2.88             | 0.48                 | 3.12            | 6.49           |
| MH32      | 342.01801  | −35.4946    | 2        | 5.16             | N/A                  | 3.83            | 8.99           |
| MH33      | 345.80901  | −31.67244   | 2        | 8.87             | N/A                  | 12.35           | 21.22          |
| MH34      | 345.16548  | −31.96997   | 2        | 9.58             | N/A                  | 13.79           | 23.38          |
| MH35      | 345.76627  | −32.54131   | 3        | 2.07             | 2.41                 | 3.52            | 8.0            |
| MH36*     | 343.76173  | −33.30183   | 1        | N/A              | 40.22                | N/A             | 40.22          |
| MH37      | 344.39038  | −33.76065   | 1        | N/A              | 30.65                | N/A             | 30.65          |
| MH38      | 342.81942  | −33.82685   | 3        | 12.03            | 0.88                 | 10.98           | 23.89          |
| MH39      | 342.83231  | −34.35561   | 2        | 76.15            | N/A                  | 45.95           | 122.09         |
| MH40      | 341.65759  | −34.4336    | 1        | N/A              | 22.44                | N/A             | 22.44          |
| MH41*     | 341.85518  | −34.60437   | 3        | 3.52             | 10.75                | 3.88            | 18.16          |
| MH42      | 343.93365  | −34.68008   | 3        | 12.98            | 9.77                 | 15.07           | 37.82          |
| MH43      | 342.72356  | −34.88700   | 1        | N/A              | 7.59                 | N/A             | 7.59           |
| MH44      | 343.73528  | −33.10917   | 2        | 8.63             | N/A                  | 14.68           | 23.31          |

**Note.** The asterisks indicate galaxies with GAMA spectroscopic redshifts.
Appendix B
Optical–Infrared Rest-frame Uncertainties in the W3 Band

In the optical–infrared window, correcting for the \((1+z)\) photometric band-shifting is not as simple as, e.g., applying a power-law scaling correction (as with the radio continuum; e.g., see Equation (2)). This is because of the varying contributions from the stellar continuum, emission lines, and ISM components (e.g., dust) that dominate in this wavelength range for the range of galaxies that are detected and characterized. The technique adopted in this study, developed by the WXSC, uses a set of templates that are compared to the optical–infrared \((0.4–22 \mu m)\) photometric SED measurements, thereby identifying the best-fit template that is then used to scale the “observed” measurements to the equivalent “rest” measurements. The list of composite templates we deploy are from Brown et al. (2014) and Spitzer-SWIRE/GRASIL (Polletta et al. 2006, Polletta et al. 2007, Silva et al. 1998), totaling over 135 composite templates that range from early-type spheroids to late-type spirals, and various AGN types. Further details of the SED template fitting are given in Jarrett et al. (2013, 2017).

In this appendix, we assess the uncertainties that arise from this rest-frame correction process. Potential sources of scatter in the rest-frame flux derivation are: (1) photometric uncertainty in the observed fluxes, (2) the number of bands that are used in the fitting process, (3) the weighting of the bands, (4) the finite number of templates and galaxy-type coverage, and (5) the dominant features in the galaxy spectrum. An example of the complexity of determining robust rest-frame corrections is shown in Figure 18, the optical–infrared SED of an active star-forming galaxy. The figure shows the before—observed fluxes and redshifted template, and after—k-corrected rest-frame fluxes with the best-fit template. This example would be considered a good \(\chi^2\) fit (with values less the 3); the NGC 2623 composite template is well-matched (although not perfect) to the actual photometric measurements for this GAMA G23 source (CATAID: 5327551). Note that the W3 k-correction is negative, i.e., the “rest” flux is fainter than the observed flux because the bright 7.7 \(\mu m\) PAH feature shifts out of the W3 band. Conversely, for W4 the correction is positive, i.e., “rest” is considerably brighter because of the steeply rising warm dust continuum that \(\lambda\)-shifts inward.

The template fitting, using inverse variance weighting, gives higher-weight to the near-infrared fulcrum from 1 to 5 \(\mu m\) because it is sensitive to the bright, evolved luminous populations that are seen in nearly all galaxy types. Since our photometric bands are wide, we are never sure about the narrow in-band features, such as the depth of the [Si] absorption features or the strength of the PAHs, for example. We are unable to estimate uncertainties due to such in-band features, but we are able to track the rest-frame repeatability that our set of templates allows.

For this we run a set of Monte Carlo random sampling trials in which slight changes to input photometry and templates may result in rest-frame fluxes that differ across trials. In each trial, we adjust the observed (input) fluxes based on their photometric error (Gaussian sigma), find the best-fit template and carry out the rest-frame corrections, and then recompute the “rest” fluxes and corresponding luminosities. For the purposes of this study, where the SFR is derived from the W3 (12 \(\mu m\)) measurements, we track the rms scatter in the W3 (12 \(\mu m\)) flux and corresponding luminosity, \(L_{W3}\). Results are shown in Figure 19, described below.

By allowing the input fluxes to vary based on their error estimates, the best-fit template may change from the original, or may remain the same, but the W3 rest flux is guaranteed to change in either case since the input changed due to random sampling of its error model. Here we are interested not in the photometric uncertainty (which is already well characterized, and propagated into our luminosity errors, etc.), but rather in how the rest flux changes relative to the input observed flux in order to gauge the template fitting uncertainties.

Through the set of sampling trials, the total \% scatter in the W3 rest versus observed fluxes is shown in Figure 19(a), where each point is a galaxy where we have measured the rms scatter in the W3 [observed–rest] flux normalized by the mean.

Figure 18. Spectral energy distribution (SED) of the GAMA source 5327551, whose redshift is 0.14314. The optical and near-IR data are from the GAMA G23 survey (green points), and the mid-IR from the WISE-WXSC (blue points). The best-fit (\(\chi = 2.4\)) template (black line) was found to be that of NGC 2623 (from Brown et al. 2014). The left panel shows the observed fluxes from GAMA G23 (optical bands, green points) and WISE-WXSC (mid-infrared, blue points). The left panel shows the observed (i.e., redshifted) fluxes, and the right panel the k-corrected rest-frame fluxes. Also shown are the WISE filter traces (scaled to unity: blue, green, orange, and red lines), as given in Jarrett et al. (2011).
observed (input) flux in the sampling distribution. This scatter, which represents the stochasticity of the template fitting itself, ranges from a few % to typically less than 10%–15% across the full redshift range of our study. There is a clear trend with redshift, likely driven by sensitivity (higher redshift galaxies tend to be fainter, but also tend to be higher luminosity, including AGNs) and mismatched template scaling errors. This translates to a scatter in the W3 luminosity, shown in Figure 19(b), also increasing with redshift. The total log $L_{W3}$ scatter is typically less than 5% for nearby galaxies ($z < 0.1$), and ranges upwards to 10% for higher redshifts, but may be much higher (20%–40%) for outliers that arise from poor template fits, either mismatched band-to-band measurements (i.e., poor colors) or simply there is no appropriate template for the galaxy. These results are encouraging: most galaxies should have only a small, <5%–10% uncertainty that arises from our optical–infrared rest-frame correction method. However, it should be noted that considerably larger errors may be induced by poor template fits.

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