Properties of AGN selected by their mid-IR colours: evidence for a physically distinct mode of black hole growth

Guinevere Kauffmann
Max-Planck Institut für Astrophysik, 85741 Garching, Germany

ABSTRACT
We study the narrow emission line properties and stellar populations of a sample of 1385 AGN selected to have strong excess emission at mid-infrared wavelengths based on comparing Wide-field Infrared Survey Explorer W1-W2 band colours with optical stellar absorption line indicators. Our goal is to understand whether the physical conditions in the interstellar medium of these objects differ from those of local AGN selected by their optical emission line ratios. To enable this comparison, we construct a control sample of 50,000 optically-selected AGN with the same redshifts that do not have strong mid-IR excess emission. The mid-IR excess and control samples differ strongly in [OIII] line luminosity, ionized gas excitation mechanism, ionization state and electron density. We show that the radio-detected, mid-IR excess AGN constitute the most luminous and highly ionized AGN in the local Universe and they contribute primarily to the growth of black holes in the most massive galaxies. At least half of this black hole growth is occurring in galaxies with recent starbursts. The morphologies of these systems indicate that the starbursts have probably been triggered by galaxy-galaxy mergers and interactions. The most luminous AGN in our mid-IR excess sample have properties that are similar to the Type II quasars studied at higher redshifts. In contrast, the control sample constitute a class of lower ionization, less luminous AGN in more quiescent galaxies that contribute primarily to the growth of low mass black holes.

Key words: galaxies:formation; galaxies:ISM; galaxies:star formation; galaxies:active

1 INTRODUCTION
Our understanding of the formation paths of supermassive black holes is currently rather sketchy. The Soltan argument (Soltan 1982) applied to the luminosity function of quasars measured at different redshifts shows that the summed emission from optically-selected AGN yields an estimate of the mass contained in “fossil quasars” that is remarkably close to the total estimated mass density in supermassive black holes at the present day (Yu & Tremaine 2002). The discovery of extremely luminous quasars at redshifts greater than 6 (Fan et al 2001), when the Universe was less than a billion years old, then implies that the most massive of these black holes, with $M_{\text{BH}} > 10^9 M_\odot$, must have formed over very short timescales. Cosmological models of black hole growth from seeds of $10^3 - 10^4 M_\odot$ show that extremely massive, high-redshift black holes cannot form unless they accrete at supercritical rates, i.e. not limited by radiation pressure of the gas, for at least part of their formation history (Volonteri & Rees 2005,2006).

Very rapid growth of black holes likely occurred primarily at relatively early epochs. The total emissivity from quasars peaks at redshifts $\sim 2 - 3$ (see Manti et al 2017 for a recent compilation of data). A census of the emission from low redshift AGN shows that most black holes in the local Universe are accreting at low rates; only a minority of the lowest mass black holes in the local Universe with masses of around $10^6 M_\odot$ are currently growing at rates that are consistent with a formation timescale of less than a Hubble time (Heckman & Kauffmann 2004). However, the existence of samples of hundreds of thousands of low redshift AGN makes it possible to search for sub-populations of objects that may be undergoing much more efficient black hole growth and where the fuelling processes may be occurring in a different mode to the bulk of the population.

In recent work, Kauffmann (2018; hereafter Paper I) introduced a new technique to identify AGN via their [3.4]-[4.6] μm (WISE W1-W2 band) colours and radio emission. A
simple procedure was introduced to pull out a “mid-IR outlier” population based on a combination of three stellar population diagnostics: the 4000 Å break strength, the specific star formation rate SFR/\(M_\odot\) and the H\(\alpha\) Balmer absorption line index. Most of these mid-IR outliers do not have centrally peaked emission and the mid-IR emission likely originates from dust spread throughout the galaxy and not from a central torus-like structure. However, in Paper I we showed that by requiring that the mid-IR outliers be detected in the Very Large Array (VLA) FIRST Survey (Radio Images of the Sky at Twenty-Centimeters; Condon et al 1991), a reasonably clean sample of AGN with centrally-peaked emission that are also identifiable as AGN using optical emission line diagnostics can be recovered.

Interestingly, the fraction of systems with clearly disturbed morphologies and signatures of recent or ongoing mergers was also very high in this sample (Figure 12 in Paper I). Although mergers and interactions between galaxies have long been hypothesized to be a means of channelling gas to the centers of galaxies and triggering accretion onto central supermassive black holes (Sanders et al 2008), clear observational evidence of a merger-triggered mode of accretion has been lacking so far. Carefully controlled studies show that once the star formation rates of AGN and non-AGN control samples are matched, there is no evidence that AGN have a higher incidence of close neighbours or asymmetric light profiles (Li et al 2008; Reichard et al 2009, Cisternas et al 2011, Villforth et al 2014). The high incidence of clearly disturbed galaxies in our sample of radio-detected, mid-IR outliers therefore motivates further study of these objects to understand whether or not they form a class of AGN distinct from the population selected by optical emission line ratios.

In this paper, we study the narrow emission line properties of a sample of 1385 radio-detected, mid-IR outliers in the main spectroscopic sample of the Sloan Digital Sky Survey in order to understand the physical conditions in the interstellar medium of these objects in more detail and to compare these with conditions in ‘ordinary’ emission-line selected AGN. We also study the stellar populations of the stars near the centers of the host galaxies of these objects using Lick index measurements of key stellar absorption features that probe stellar ages, metallicities and \(\alpha\) to Fe element abundance ratios. We interpret our findings using photo-ionization and stellar population synthesis models. Finally, we examine the contribution of radio-detected, mid-IR outliers to the total black hole growth in the local Universe as a function of host galaxy stellar mass and star formation history, as well as the ionization state of the narrow-line region (NLR) gas in these systems.

This paper is structured as follows. In section 2, we review our sample selection criteria as well as the measurements of the emission and absorption line quantities used in this work. In section 3, we present a series of emission line diagnostic diagrams useful for understanding the physical conditions in the ionized gas in our samples. In section 4, we study the stellar populations of the host galaxies of our radio-detected mid-IR outliers as well as our control sample of AGN, and in section 5, we examine the contribution of the mid-IR outliers to the total growth of black holes at the present day. In section 6, we discuss similarity and differences of these results to those obtained in past studies of Type II quasars, compact steep spectrum radio sources and radio galaxies in the IRAS catalogue. Section 7 presents a summary of our findings and a discussion of future perspectives.

## 2 CONSTRUCTION OF THE SAMPLES

As described in detail in Paper I, all the samples are constructed from a magnitude-limited sample of 533,731 galaxies located in the main contiguous area of the final Data Release (DR7; Abazajian et al 2009) of the main spectroscopic survey carried out by the Sloan Digital Sky Survey in the northern Galactic cap. The galaxies are selected to have \(r < 17.6, 24 < M_r < -16\) and spectroscopically measured redshifts in the range 0.001 < \(z\) < 0.5. Here \(r\) is the \(r\)-band Petrosian apparent magnitude, corrected for Galactic extinction, and \(M_r\) is the \(r\)-band Petrosian absolute magnitude, corrected for evolution and K-corrected to its value at \(z=0.1\).

This sample is then cross-correlated with the AllWISE Source Catalog, which contains astrometry and photometry for 747,634,026 objects detected on the deep AllWISE Atlas Intensity Images. 533,612 galaxies from the original sample are detected in both the W1 and W2 bands, i.e. there is a 99.97% detection rate. Paper I introduces a method for selecting so-called red outliers in the plane of SFR/\(M_\odot\) versus \(D_n(4000)\) space for galaxies with log SFR/\(M_\odot\) > 11 and in H\(\alpha\) versus \(D_n(4000)\) space for galaxies with lower specific star formation rates. Galaxies were binned in these two planes and the outliers were selected as galaxies with W1-W2 colours lying above the 95th percentile points in each bin.

Examination of the central colour gradients of 996 of the nearest of these outliers indicated that radio luminosity was the property most predictive of redder W1-W2 colours near the center of the galaxy, as would be expected if the hot dust emission originated mainly from a central torus. Radio luminosities were obtained by cross-correlating the full DR7 galaxy sample with the FIRST Survey with a positional matching tolerance of 3 arcsec (see Paper I for more details). We note that only \(\sim 1\)% of the mid-IR outlier sample are detected at radio wavelengths, making the radio selection a critical aspect of our technique compared to previous work. As we will show, the combined mid-IR/radio selection yields a sample of AGN with optical emission line luminosities that are much higher than a “control” sample of AGN selected without regard to their radio or mid-IR properties. This is unexpected, because pure radio selection yields samples that are biased towards the most massive elliptical galaxies with little ongoing star formation and optical emission line activity (Best et al 2005a,b).

In this paper, we work with two samples:

- **Radio-detected, mid-IR excess AGN** A sample of 1386 galaxies with stellar masses in the range 10.0 < log \(M_\odot\) < 11.8, redshifts less than 0.25 and with radio luminosities greater than 10^{22.5} Watts Hz^{-1}, with Ho luminosities log \(L(H\alpha)\) > 5.5 L_\odot and with both H\(\alpha\) and H\(\beta\) detected with \(S/N > 3\). Unless indicated otherwise, all emission line and 1

1Note that in Paper I, we showed that 80% of all radio-detected,
stellar absorption line properties are taken from the MPA-JHU release of spectrum measurements for DR7 galaxies. These are based on methods described in Brinchmann et al (2004) and Tremonti et al (2004).

- A control sample of optical AGN The control sample is selected so as to remove AGN that have significant excess emission at mid-IR or radio wavelengths. We pull out a sample of 50,084 optically-selected AGN that have W1-W2 colours that do not place them into the “mid-IR excess category” and that are also not detected in the FIRST catalogue of radio sources. They are further selected to have stellar masses, redshifts and Hα luminosities in the same range as the radio-detected, mid-IR excess AGN sample.

We note that a galaxy is defined to be an optically-selected AGN according to the demarcation in [OIII]/Hβ and [NII]/Hα emission line ratios given in Kauffmann et al (2003b):

\[
\log ([\text{OIII}]/H\beta) > 0.61/\log([\text{NII}]/H\alpha) - 0.05 + 1.3 \quad (1)
\]

This cut yields a larger optical AGN sample than that of Kewley et al (2001) and allows us explore AGN over a larger dynamic range in properties such as ionization parameter. In the following sections, we compare and contrast the emission and stellar absorption line properties of these two samples.

Note that there are in total about 121,000 galaxies in this stellar mass and redshift range in our sample that are classified as AGN without mid-IR excess. It is the Hα luminosity and Hβ S/N cuts that are responsible for reducing the number of control AGN down to ~ 54,000 objects, i.e. we are excluding the AGN with the weakest emission lines from this comparison. Many weak emission line objects are classified as LINERs in BPT line ratio diagnostic diagrams, but it has been shown that most of the weak emission is likely to originate from ionization of gas by evolved stars such as planetary nebulae (Capetti & Baldi 2011; Singh et al 2013; Belfiore et al 2016). The cut on galaxies with radio detections removes a further ~ 4000 objects. Since this is a small fraction of the total sample, we do not attempt to implement radio luminosity thresholds that scale with properties of the galaxy, such as star formation rate.

3 PHYSICAL CONDITIONS IN THE INTERSTELLAR MEDIUM DEDUCED FROM EMISSION LINES

3.1 Excitation mechanism

In Figure 1, we begin with a set of classic emission line diagnostic diagrams from BPT and from Veilleux & Osterbrock (1987), which have been constructed to probe whether the excitation source is an AGN or a starburst. The first of these diagnostic diagrams, log [OIII]/Hβ versus log [NII]/Hα was used to select our optical AGN “control” sample shown as black points in the top left panel of the figure. The red points show the radio-detected, mid-IR excess AGN and the demarcation between AGN and star-forming galaxies is shown as a green curve on the diagram. Note that to make this figure, we have selected a random sample of 1400 out of the 50,085 control galaxies, so that the density of red and black points is the same in each panel.

As can be seen, the majority of the black points cluster in the vicinity of the green locus, indicating that a substantial fraction of the ionizing photons for AGN in the control sample likely originate from HII regions in the galaxy. The red points are spread much more widely over this diagram. In addition, there are many systems that have [OIII]/Hβ ratios close to 10, which indicates that the ionizing photons in the mid-IR excess AGN likely originate from a source with a power-law spectrum at UV/X-ray wavelengths, such as an accretion disk.

The top-right and bottom-left panels show two additional diagnostic diagrams that were extensively studied by Kewley et al (2006), who showed that there were two clearly separated branches – one corresponding to the high-ionization Seyferts and another corresponding to lower ionization sources, among them LINERs (low-ionization narrow emission line sources). The boundaries between the two classes derived by Kewley et al are shown as green lines in the two panels. As can be seen, most galaxies in control sample cluster in the low-ionization branch, and are located close to the region occupied by star-forming galaxies. The radio-detected, mid-IR excess AGN lie mainly on the upper, high-ionization branches in these two diagrams, and are more widely spread.
power law radiation field

AGN is uncertain. In photo-ionization models of AGN, the intrinsic ionizing spectral energy distribution (SED) in AGN is often assumed, with $F_\nu \propto \nu^{\alpha}$ is often assumed, with $\alpha$ a free parameter. However, as discussed in the previous section, in many AGN, ionizing photons may originate both from a combination of power-law sources and young, massive stars.

The left panel of Figure 2 shows a slightly revised version of one of the proposed SED diagnostic diagrams in a recent paper by Richardson et al (2014), which combines a number of emission lines from the element oxygen from different ionization states. Note that [OII], [OIII] and [OI] have ionization energies of 13.6, 35.1 and 54.9 eV, respectively. [OIII] is a weaker line and is not detected in all the galaxies in our two samples. For this reason, the entire control sample, rather than just a random subset, is plotted in the figure. As seen in the previous figure, the majority of galaxies in the control sample lie on a sequence bounded by low [OIII]/[OII] ratios. Interestingly, the mid-IR excess sample scatters to the higher [OIII]/[OII] ratios at low values of [OII]/[OII]. We note that 80% of the objects in the mid-IR excess sample have high S/N [OII] detections, but only 50% of the control sample galaxies are detected in [OII]. Most of the non-detected galaxies are low ionization systems. This means that the actual shift of mid-IR excess objects towards higher ionization states is stronger than is already apparent from this diagram.

Since the ionization energy of [OII] is nearly identical to that of hydrogen, in an ionization-bounded nebula [OII] is produced predominantly in the “partially ionized zone”, wherein both neutral oxygen and free electrons coexist (Ho 2008). In starburst galaxies, [OII] originates in regions of the galaxy containing luminous young stars, while in powerful Seyfert galaxies [OIII] is often seen to map out cone-like structures of outflowing, ionized gas (see for example Fogge 1988, Ferguson et al 1997). One interpretation of the difference between the red and the black points, therefore, may be the relative strength of the ionization cones in the two classes of objects. We will come back to this hypothesis later when we look at how the stellar populations of the underlying host galaxy and the intrinsic luminosity of the AGN vary in different regions of this diagram.

Levesque & Richardson (2014) have proposed the [NeIII]/[OII] ratio as an alternative ionization parameter diagnostic in star-forming galaxies. Neon closely tracks the oxygen abundance in star-forming galaxies and HII regions and is one of the principal coolants along with oxygen in the ionized interstellar medium. [NeIII] has a higher ionization energy than [OII], so that the relation between [NeIII]/[OII] and [OIII]/[OII] serves as a diagnostic of changes in the shape of the UV radiation field in different galaxies. Finally, ionized neon is abundant over a broader range of distances from the ionizing source in an ionized nebula than ionized oxygen. This means that the [NeIII]/[OII] ratio will be more sensitive to very high ionization parameters than [OIII]/[OII].

The right panel of Figure 2 shows the location of the control AGN (black points) and the radio-detected, mid-IR excess AGN in the plane of [NeIII]/[OII] versus [OIII]/[OII]. We note that more than two thirds of the mid-IR excess AGN have high S/N [NeIII] detections, but [NeIII]/[OII] can only be measured for only ~10% of the control sample. Nevertheless, there are very clear differences in the locations of these two AGN populations in this diagram. The control sample AGN appear to populate two sequences: one where the [OIII]/[OII] ratio stays fixed around 0.5, but the [NeIII]/[OII] ratio varies by an order of magnitude, and another where [OIII]/[OII] and [NeIII]/[OII] correlate roughly linearly. The mid-IR excess AGN only populate the second of these sequences.

In Figure 3, we plot the [NeIII]/[OII] ratio as a function of the AGN luminosity as measured by the Hα luminosity (left) and the [OIII] luminosity of the galaxy. The mid-IR excess AGN are displaced towards [OIII] luminosities that are, on average, an order-of-magnitude higher than those of the control sample AGN. The displacement of the mid-IR excess AGN to higher [NeIII]/[OII] ratios is most evident for mid-IR excess AGN with [OIII] luminosities greater than $10^8 L_\odot$. We will study these very high-luminosity, high-ionization parameter systems in more detail in section 6 of this paper.

3.3 Interstellar Medium Metal Abundances

Figure 4 shows ratios of lines with similar ionization potentials, but from different elements, leading to metal abundance sensitivity. Both AGN samples span roughly the same range in [NI]/Hα, [SII]/Hα, [SIII]/Hα and [OII]/Hα, showing that the metallicity of the ionized gas in these systems is about the same.
3.4 Interstellar Medium Electron Densities

Electron density, \( N_e \), is one of the key physical parameters characterizing an ionized gaseous nebula. The electron density in an ionized gaseous nebula can be measured by observing the effects of collisional de-excitation on nebular (forbidden) emission lines. This is usually achieved by comparing the observed intensities of lines emitted from two different energy levels of nearly equal excitation energy from the same ion. If the two levels have different radiative transition probabilities, then the relative populations of the two levels will vary with electron density, as will the intensity ratio of transitions emitted from them. In the optical wavelength region, a commonly used density-diagnostic ratio is \([\text{SII}]\lambda 6716/\lambda 6731\), lower values of this ratio being indicative of higher electron densities.

In Figure 5, we plot the \([\text{SII}]\lambda 6716/\lambda 6731\) doublet ratio as a function of \([\text{OIII}]\) line luminosity (left) and the \([\text{OIII}]\)/[OII] ionization parameter (right) for our two AGN classes. As seen previously, the mid-IR AGN are clearly offset towards higher \([\text{OIII}]\) luminosities and ionization parameters compared to the control sample. There is also a clear trend for the electron densities to increase in more luminous AGN with higher ionization parameters. Overall, \( N_e \) is higher in the mid-IR excess sample than in the control sample.

3.5 Dust in the Interstellar Medium

Given that the interstellar medium electron densities in the mid-IR excess AGN are higher and that the excess mid-IR radiation in these systems likely originates from dust grains heated to high temperatures, one might ask whether radiation pressure from dust grains plays a more important role in determining the emission line properties of these systems compared to more "normal" AGN.

Dopita et al. (2002) developed models for the narrow line regions of AGN where dust and the radiation pressure acting upon it provide the controlling factor in moderating the density, excitation, and surface brightness of photoionized NLR structures. Additionally, photoelectric heating by the dust is important in determining the temperature structure of the models. In later work (Groves et al 2004b), the dusty models were compared with simpler isochoric (constant density) dust-free models in a series of line ratio diagram in an attempt to identify clear tests of the models.

In the left panel of Figure 6, we present a diagram that...
was first introduced by Binette et al (1996) as a way of motivating the need for photo-ionization models with complex gas density structure, as might be expected in dusty regions of the galaxy. Groves et al (2004b) showed that the Dopita et al (2002) models where the gas density is controlled by radiation-pressure from dust produce significantly higher [HeII]/Hβ ratios when the ionization parameter is large compared to models without dust. Note that because [HeII]λ4686 measurements are not available from the MPA/JHU database, we have used measurements of this line provided by the Portsmouth release of spectrum measurements (Thomas et al 2013).

The main result from the comparison of our two AGN samples is that the mid-IR excess AGN and the control sample overlap almost exactly in [HeII]/Hβ at large values of [OIII]/Hβ. In the right panel of Figure 6, we superpose the dust-free isochoric models of Groves et al (2004a) on the data. Magenta lines indicate the locus of models with different ionization parameter for solar metallic gaslicity, while blue lines are for 0.2 solar models. The differences between the solid and dashed lines show the effect of changing the shape of spectrum of the ionizing radiation – solid lines are for a flat power law spectrum (α = −1.2, Fν ∝ να), while dashed lines are for a steep power-law spectrum (α = −2) with less contribution at shorter wavelengths. As can be seen, the extremely simple dust-free models with constant density are able to fit the data remarkably well at large values of [OIII]/Hβ. We thus conclude that there is no evidence that dusty NLR models provide an explanation for differences in the emission line properties of our mid-IR excess and control AGN samples.

In the data, the most extreme values of [HeII]/Hβ are found for AGN in the control sample and they occur at low values of [OIII]/Hβ. None of the Groves et al photo-ionization models pass through this region of parameter space. This may indicate that some other gas heating mechanism may be at work in these objects.

4 THE PHYSICAL ORIGIN OF THE HIGH IONIZATION GAS IN MID-IR EXCESS AGN

In the previous section, we showed that the ionized gas in the mid-IR excess AGN and in the control sample differ markedly in luminosity, excitation mechanism, ionization state and electron density, but that the ionized gas metal abundances are quite similar in the two samples and that there is no evidence that radiation pressure from dust plays a more important role in regulating the densities of the narrow-line regions of the mid-IR excess objects. In this section, we examine the stellar populations and the radio properties of the two AGN classes in detail in order to understand whether the presence or absence of young, massive stars and/or radio jets play any role in the observed differences.

4.1 Clues from stellar absorption lines

In this section we examine relations between the following stellar absorption line diagnostics:

(i) The 4000 Å break, Dn(4000). The break occurring at 4000 Å is the strongest discontinuity in the optical spectrum and arises because of the accumulation of a large number of spectral lines in a narrow wavelength region. In hot stars, the elements are multiply ionized and the opacity decreases, so the 4000Å break will be small for young stellar populations and large for old, metal-rich galaxies. We use the definition of the break defined in Balogh et al. (1999) as the ratio of the average flux density Fν in the bands 3850-3950 and 4000-4100 Å and we will denote this index as Dn(4000).

(ii) Strong Hδ absorption lines arise in galaxies that experienced a burst of star formation that ended 0.1-1 Gyr ago. Worthey & Ottaviani (1997) defined an HδA index using a central bandpass bracketed by two pseudo-continuum bandpasses. Kauffmann et al (2003a) and Kauffmann (2014) showed that the location of a galaxy in the plane of HδA versus Dn(4000) could be used to distinguish galaxies that have experienced a recent burst of star formation from galaxies that have had continuous star formation histories over the past 1-2 Gyr.

(iii) The total metallicity-sensitive index [MgFe]'. Several studies have addressed the dependence of Lick index strengths on changes in the relative ratios of heavy elements (e.g. Tripicco & Bell 1995; Thomas, Maraston & Bender 2003) These studies have led to the identification of composite Mg + Fe indices, which are sensitive to total metallicity (i.e. the fraction by mass of all elements heavier than helium over the total gas mass) but show little sensitivity to α/Fe (i.e. the ratio of the total mass of elements to the mass of iron). In this work, we use

\[
[MgFe]' = \sqrt{Mgb(0.72Fe5270 + 0.28Fe5335)}
\]

as proposed by Thomas et al. (2003).

(iv) The magnesium-sensitive index Mgb. The location of a galaxy in the plane of Mgb versus [MgFe]' should then provide an indication of the α-enhancement of the stellar population.

Figure 7 shows the location of our two classes of AGN in the planes of HδA versus Dn(4000), Mgb versus Dn(4000), [MgFe]' versus Dn(4000) and [MgFe]' versus Mgb. The mid-IR excess AGN are seen to populate regions of these planes that are largely empty of AGN from the control sample. The first panel shows that the mid-IR excess AGN include many galaxies with with low values of Dn(4000) and high values of HδA that have likely experienced recent bursts of star formation. We will show quantitatively in Section 5 the degree to which starburst activity is boosted in this population compared to the control sample. The second and third panels show that these bursty galaxies have low metallicities. The fourth panel shows that the Mgb index is somewhat stronger at a fixed value of [MgFe]' for the mid-IR excess AGN, indicating that their stellar populations are more enhanced with α-elements. Again, this is exactly what would be expected if some of these systems have experienced recent starbursts.

4.2 Relationship between star formation history and ionization state

We now examine how the ionization state of the gas in the mid-IR excess sample varies in the 4 stellar population diagrams shown in Figure 7. In Figure 8, we split the sample into 3 different ranges in log[NeIII]/[OII]: AGN with
Properties of AGN selected by mid-IR Colours

Figure 7. Stellar absorption line index diagrams comparing the stellar population properties of the host galaxies of mid-IR excess AGN (red points) with control sample AGN (black points). Galaxies are shown in the planes of H$\delta_A$ versus $D_n$(4000) (top left), Mg$b$ versus $D_n$(4000) (top right), $[\text{MgFe}']$ versus $D_n$(4000) (bottom left) and $[\text{MgFe}']$ versus Mg$b$ (bottom right).

$\log [\text{NeIII}]/[\text{OII}] > -0.6$ are colour-coded blue, those with $-0.9 < \log [\text{NeIII}]/[\text{OII}] < -0.6$ are colour-coded in black and those with $\log [\text{NeIII}]/[\text{OII}] < -0.9$ are colour-coded in magenta. We see from this figure that the galaxies with the lowest $[\text{NeIII}]/[\text{OII}]$ values coloured in magenta have young, metal-poor stellar populations.

In Figure 9, we expand upon this result by colour-coding AGN in the plane of $[\text{NeIII}]/[\text{OII}]$ versus $[\text{OIII}]/[\text{OII}]$ according to their $D_n$(4000) values. Magenta points indicate galaxies with $1.6 < D_n$(4000) < 1.8 , red points indicate galaxies with $1.4 < D_n$(4000) < 1.6, green points galaxies with $1.2 < D_n$(4000) < 1.4 and blue points galaxies with $1.0 < D_n$(4000) < 1.2. Results are shown separately for control sample AGN and for mid-IR excess AGN. We note that galaxies that are colour-coded blue have $D_n$(4000) values that cannot be explained unless their present-day star formation rates are elevated compared to their past average ones, i.e. they are currently experiencing a burst of star formation (Kauffmann 2014).

Very similar patterns of variation in $D_n$(4000) are seen for the control sample AGN and for the mid-IR excess AGN in Figure 9. Galaxies with $[\text{NeIII}]/[\text{OII}]$ values greater than $\sim 0.1$ have predominantly old stellar populations. Starburst galaxies (blue points) have low $[\text{NeIII}]/[\text{OII}]$ values in both samples. The relation between $D_n$(4000) and $[\text{OIII}]/[\text{OII}]$ is more complex. Galaxies with old stellar populations occupy a wide range in $[\text{OIII}]/[\text{OII}]$ ratio in both samples. It is only the young starburst galaxies that can clearly be distinguished by their low $[\text{OIII}]/[\text{OII}]$ values.

Figure 8. The mid-IR excess AGN plotted in Figure 7 are colour-coded according to $[\text{NeIII}]/[\text{OII}]$. AGN with $\log [\text{NeIII}]/[\text{OII}] > -0.6$ are plotted as blue triangles, those with $-0.9 < \log [\text{NeIII}]/[\text{OII}] < -0.6$ as black squares and those with $\log [\text{NeIII}]/[\text{OII}] < -0.9$ as magenta circles.

Figure 9. AGN in the plane of $[\text{NeIII}]/[\text{OII}]$ versus $[\text{OIII}]/[\text{OII}]$ are colour-coded according to their $D_n$(4000) values. Magenta points indicate galaxies with $1.6 < D_n$(4000) < 1.8 , red points indicate galaxies with $1.4 < D_n$(4000) < 1.6, green points galaxies with $1.2 < D_n$(4000) < 1.4 and blue points galaxies with $1.0 < D_n$(4000) < 1.2. Results are shown separately for control sample AGN (left) and for mid-IR excess AGN (right).

4.3 Relationship between AGN luminosity and ionization state

In Figure 10, we colour-code AGN in the plane of $[\text{NeIII}]/[\text{OII}]$ versus $[\text{OIII}]/[\text{OII}]$ according to their $[\text{OIII}]$ line luminosities. Black points indicate AGN with $5 < \log L[\text{OIII}] < 6$ , red points indicate AGN with $6 < \log L[\text{OIII}] < 7$, green points AGN with $7 < \log L[\text{OIII}] < 8$ and blue points AGN with $8 < \log L[\text{OIII}]$. Once again, the control sample is shown in the left panel and the mid-IR excess AGN in the right panel. Because the cuts on AGN...
luminosity have been made using the [OIII] line, it is natural to expect that high luminosity and low luminosity AGN will segregate along the x-axis of the plot. Interestingly, there is only a weak relation between [NeIII]/[OII] ratio and AGN luminosity for the control sample, but in the mid-IR excess sample we clearly see that the highest luminosity systems with log L[OIII] > 8 have very high [NeIII]/[OII].

Moreover, these very high luminosity systems lie on a remarkably tight locus in the [NeIII]/[OII] versus [OIII]/[OII] plane.

In the previous subsection, we found that AGN with very high [NeIII]/[OII] have predominantly old stellar populations in their central regions as measured by their D_n(4000) break strengths. Note that at the mean redshift of the sample (z ∼ 0.1), the 3 arcsec SDSS fibre spectrum subtends a physical region of radius 2.8 kpc at the center of the galaxy, i.e. the spectrum is indicative of the mean age of the stellar population of all the stars in the bulge. It is still possible that a smaller population of young, very massive stars concentrated in the vicinity of the central supermassive black hole is responsible for the ionization of [NeIII], as has been found in the bulge of our own Milky Way (Serabyn, Shupe & Figer 1998).

To explore this hypothesis in more detail, we turn to the stellar photo-ionization grids of Levesque & Richardson (2014), which predict the relation between [NeIII]/[OII] and [OIII]/[OII] for the ionized gas in the vicinity of a population of young massive stars over a very large range in ionization parameter. The models in Levesque & Richardson (2014) are an update of the Levesque et al (2010) models, which span a range of ionization parameters 10^7 cm s^{-1} < q < 4 × 10^8 cm s^{-1} chosen to agree with observed ionization parameters in local starburst galaxies. Richardson et al (2013) extended these models from q values of 6 × 10^8 cm s^{-1} up to the theoretical maximum of q_{max} = c. This was done in order to provide models that could better fit the emission line properties of strongly star-forming galaxies at high redshifts.

In the left panel of Figure 11, we plot the relations between [NeIII]/[OII] and [OIII]/[OII] given in Table 1 of Levesque & Richardson (2014) together with the data for the most luminous mid-IR excess AGN with log L[OIII] > 8. Model results are shown for 5 different metallicities (Z=0.001, cyan; Z=0.004, green; Z=0.008, black, Z=0.020, red; Z=0.040, magenta).

![Figure 10. AGN in the plane of [NeIII]/[OII] versus [OIII]/[OII] are colour-coded according to [OIII] line luminosity. Black points indicate AGN with 5 < log L[OIII] < 6, red points indicate AGN with 6 < log L[OIII] < 7, green points AGN with 7 < log L[OIII] < 8 and blue points AGN with 8 < log L[OIII]. Results are shown separately for control sample AGN (left) and for mid-IR excess AGN (right).](image1)

![Figure 11. Left panel: The relations between [NeIII]/[OII] and [OIII]/[OII] given in Table 1 of Levesque & Richardson (2014) are plotted together with the data. The most luminous mid-IR excess AGN with log L[OIII] > 8 are highlighted as larger filled blue circles. Model results are shown for 5 different metallicities (Z=0.001, cyan; Z=0.004, green, Z=0.008, black, Z=0.020, red; Z=0.040, magenta). Right panel: [NeIII]/[OII] is plotted as a function of the ionization parameter q for the different models.](image2)
[OIII] luminosities are very different for the two classes of AGN. We now illustrate this point quantitatively. Because our two AGN samples are drawn from a complete r-band magnitude limited sample of galaxies, it is simple to calculate the relative number densities of AGN in the two classes by weighting each galaxy by 1/Vmax where Vmax is the total volume over which the galaxy can be detected in the survey. The left hand panel of Figure 13 shows the logarithm of the ratio of the number density of mid-IR excess AGN to that of AGN in the control sample as a function of [OIII] line luminosity. The black points show results for the measured [OIII] line fluxes without any extinction correction. The red points show the effect of correcting the [OIII] line flux for extinction using the measured Balmer decrement. As can be seen, for low luminosity AGN with [OIII] line luminosities \( \sim 10^6 - 10^7 L_\odot \), control sample AGN are 30-1000 time more numerous than mid-IR excess AGN. For [OIII] line luminosities greater than \( 10^7 L_\odot \), the number density of mid-IR excess AGN begins to exceed the number density of control sample AGN.

The right-hand panel of Figure 13 shows the ratio of the integrated [OIII] luminosity in the two classes as a function of the stellar mass of the host galaxy. This plot follows the approach taken in Heckman & Kauffmann (2004), where the [OIII]5007 line was used as a proxy for black hole accretion rate and the integral over the [OIII] luminosities of a sample of galaxies represented the total contribution of the population to black hole growth in the local Universe. For galaxies with stellar mass comparable to that of the Milky Way (i.e. \( \log M_\star = 10.6 \)), we find that the total [OIII] luminosity contributed by the mid-IR excess population is around a quarter of that contributed by the control sample AGN. The relative contribution from the mid-IR excess AGN increases with stellar mass and for galaxies that are 10 times more massive than the Milky Way, mid-IR excess AGN contribute as much integrated [OIII] luminosity as the control sample.

In Figure 14, we illustrate two more ways in which the mid-IR AGN and the control AGN differ. In the top panels, the solid lines show how the total integrated [OIII] luminosity from AGN is partitioned as a function of stellar mass of the host galaxy. Results for the control sample are shown in the top left panel and for the mid-IR excess sample in the top right panel. In both samples, most of the integrated [OIII] emission is located in galaxies with masses close to that of the Milky Way (i.e. \( \log M_\star \sim 10.6 \)). The much larger number densities of control sample AGN at these stellar masses shown in Figure 13 tells us that the duty cycle of this mode of accretion is much longer. This point can also be made by looking at the contribution of galaxies that have undergone a recent burst of star formation to the integrated [OIII] luminosity in both samples. This is shown by the dashed curves in each of the top two panels.

In order to divide galaxies into bursting and non-bursting classes, we use a grid of model star formation histories that fit to the measured values of \( D_\alpha(4000) \) and H\( \delta_A \). The reader is referred to Kauffmann (2014) for more details about this methodology. In summary the model library includes models with continuous star formation histories, models with ongoing bursts and models with bursts that have occurred between 0.2 and 2 Gyr in the past. Continuous models occupy a narrow locus between the regions of the \( H_\delta_A \) versus \( D_\alpha(4000) \) diagram spanned by the two classes of burst models. Model galaxies with ongoing bursts are displaced to lower \( H_\delta_A \) values at fixed \( D_\alpha(4000) \), whereas model galaxies with a past burst are displaced to higher \( H_\delta_A \). We first search the continuous star formation library for the model that minimizes \( \chi^2 \). We use the minimum \( \chi^2 \) value to assess whether the continuous star formation history probability has greater than 50% probability of being correct. If not, we then search both the ongoing and past burst libraries for a new minimum \( \chi^2 \) model. If the new minimum is smaller than that obtained for the continuous library, the classification as a starburst system is considered as “secure”.

A comparison of the dashed curves in the top left and right panels of Figure 14, shows that the contribution of galaxies with starbursts to the total [OIII] luminosity is a

---

2 To correct for extinction, we adopt the \( A_\lambda = 1.9655R_\lambda \log(H_\alpha/H_\beta/2.87) \), where we assume \( R_\lambda = 3.1 \) and adopt the extinction curve given in equation (3) of Wild et al (2007) with \( \mu = 0.3 \).
6 RELATION OF MID-IR EXCESS AGN SAMPLE TO OTHER SAMPLES FROM THE LITERATURE

In this section, we briefly discuss similarity and differences of the results presented in this paper to those obtained in past studies of a variety of low-redshift luminous AGN, including compact steep spectrum radio sources, radio galaxies with detections in the Infrared Astronomical Satellite (IRAS) catalogue and Type II quasars. In addition, we clarify how our sample differs from AGN samples selected only by their mid-IR colours.

6.1 Compact steep-spectrum radio sources

The gigahertz peaked-spectrum (GPS) and compact steep-spectrum (CSS) radio sources make up significant fractions of the bright (centimeter-wavelength-selected) radio source population (10% and 30%, respectively). The GPS sources are powerful (log P(1.4Ghz) > 25 W Hz$^{-1}$) and compact (<1 kpc). The CSS sources are just as powerful, but are larger (1-20 kpc in size). The GPS and CSS sources are believed to be the be the younger stages of powerful larget-scale radio sources.

The host galaxy morphologies of CSS sources have been studied by Gelderman & Whittle (1994) and evidence has been found for diffuse linear features, such as tidal tails, bridges, and shells, indicative of a recent interaction. Gelderman & Whittle present low-dispersion spectra (and high-dispersion spectra of the region around [O III]$\lambda$5007) of a sample of 20 CSS sources (both galaxies and quasars). The main result is that the CSS sources have relatively strong, high equivalent width, high-excitation line emission, with broad, structured [O III] profiles. They suggest that these properties are consistent with strong interactions between the radio source and the ambient line-emitting gas. Holt, Tadhunter & Morganti (2009) also find a preponderance of complex, multi-component emission lines in compact radio galaxies, which they interpret in terms of jet-cloud interactions. Clear correlations are observed between the total radio luminosities of the sources and their [OIII] line luminosities, lending further support to this picture.

Our sample of radio-detected mid-IR excess sources is quite different. Firstly, the radio luminosities of our objects are all less than $10^{25}$ W Hz$^{-1}$ and as shown in Figure 12, there is no correlation between radio and [OIII] line luminosity. Second, the emission lines in our objects are narrow and there is no evidence for velocity shifts indicative of large gas motions in the majority of our objects (see Paper I).

6.2 Radio-excess IRAS galaxies

The selection of radio-excess IRAS galaxies was described in a paper by Drake et al (2003). Objects were found by cross-correlating the Parkes-MIT-NRAO 5 GHz radio source catalogue with the IRAS Faint Source Catalogue. Objects having more than 5 times as much radio emission as expected from the FIR-radio correlation followed by normal star-forming galaxies were selected to form the radio excess sample. The radio luminosities are in the range $23.5 < \log P(5\text{Ghz}) < 26$, i.e. more luminous on average than our mid-IR excess sources.
sources, but less luminous than the CSS and GPS sources discussed above.

Follow-up optical spectroscopy is discussed in a paper by Buchanan et al (2006). These authors find that the radio excess is an excellent indicator of the presence of high excitation optical emission lines, indicative of the presence of an optical AGN. As in the GPS and CSS sources, the emission lines are often broad with complex structure. There is evidence for jet-cloud interactions in the form of blue-shifted lines in some of the sources. Finally, a significant fraction of the sample show post-starburst stellar continua.

We note that our galaxies have been selected to have a clear mid-IR excess rather than a radio excess, so it is perhaps not surprising that classical optical signatures of radio jets interacting with the ISM are largely missing. It remains to be understood if the radio emission in the mid-IR excess AGN may be stellar in origin. We also note that the redshifts of the radio-excess IRAS AGN and the CSS/GPS sources studied in the literature are in general higher than the galaxies in our two samples.

### 6.3 Type II Quasars

Type II quasars are the obscured counterparts of the classical quasar population predicted by AGN unification models. In the optical, Type II quasar candidates are traditionally selected as objects with narrow permitted emission lines and high ionization line ratios. Zakamska et al (2003) were the first to compile large samples of Type II quasar candidates in the Sloan Digital Sky Survey. Their objects were selected to lie in the redshift range of $0.3 < z < 0.83$ in order to disfavour selection of low luminosity objects. The main disadvantage of applying such a redshift cut in SDSS is that the Type II quasars are not selected from a magnitude-limited survey of galaxies, so their demographics and contribution to black hole growth cannot be studied in detail, nor can direct comparisons be made to other classes of AGN.

Zakamska et al's Type II selection was based on a cut in the $[\text{OIII}]/\text{Hβ}$ line ratio as well as the presence of very high-ionization lines such as [NeV]. The $[\text{OIII}]$ line luminosities of the sample range from $3 \times 10^7 \, L_\odot$ to close to $10^{10} \, L_\odot$ and the $[\text{OIII}]/\text{Hβ}$ line ratios lie in the range 1–10, i.e. very similar to the most luminous objects in our sample. In follow-up work, Zakamska et al (2004) found that 143 of these objects had counterparts in the FIRST radio catalogue. They speculate that this may represent an overestimate of the true fraction, because the SDSS targeted many FIRST radio sources for spectroscopy. Hubble Space Telescope imaging of the host galaxies of a subset of 9 Type II quasars with $[\text{OIII}]$ line luminosities greater than $3 \times 10^9 \, L_\odot$ reveal that 6 out of the 9 are elliptical galaxies well-fit by de Vaucouleurs light profiles and the other 3 have a minor disk component (Zakamska et al 2006). Most recently, Liu et al (2013a,b) have obtained IFU data for 11 of the most luminous, radio-quiet objects in their sample and show that the $[\text{OIII}]$ emission is very extended with a mean diameter of 28 kpc and is spherical in morphology. The majority of nebulae show blue-shifted excesses in their line profiles across most of their extents, signifying gas outflows. These authors estimate a median outflow velocity of 760 km/s, similar to or above the escape velocities from the host galaxies.

In Figure 15, we present a compilation of images of the mid-IR excess AGN in our sample with the highest $[\text{OIII}]$ luminosities ($> 10^8 \, L_\odot$). As can be seen, the majority also have elliptical morphologies and centrally concentrated light profiles. The galaxy in the bottom row with a strange red handle-like protuberance is the famous “teacup” AGN, the nearest known radio-quiet type II quasar with a redshift $z=0.08056$, first identified by Reyes et al (2008). In recent work, Harrison et al (2015) have studied the ionized gas kinematics in this object and find evidence for an outflow with velocity 740 km/s. We thus believe it is likely that there is a close correspondence between the Type II quasar population and the brightest objects in our mid-IR excess sample. We have also checked whether there is a significant population of optically-selected AGN with $[\text{OIII}]$ luminosities greater than ($> 10^8 \, L_\odot$) that are not included in our mid-IR-excess sample. We find only 25 out of 128 such objects, indicating that the mid-IR and type II quasar selection techniques yield essentially the same set of objects at the very highest $[\text{OIII}]$ luminosities.

What about the less luminous mid-IR excess AGN? In Figure 16, we present a compilation of objects with $D_n(4000)$ in the range 1.0–1.2, indicative of current bursts of star formation. As shown in Figures 9 and 10, these galaxies have more moderate $[\text{OIII}]$ luminosities in the range $10^7 – 10^8 \, L_\odot$. As can be seen, there are many more interacting pairs and triples in this sample than in the high-luminosity sample. If the galaxies in Figures 15 and 16 constitute different phases of the same merger-induced black hole fuelling events, the host galaxies shown in Figure 16 could be said to be an earlier stage of the merging process.

### 6.4 AGN selected only by a mid-IR colour criterion

As discussed in Paper I, the selection of AGN using WISE photometry has generally been carried out using colour cuts designed to avoid the main locus of star-forming galaxies (e.g. Stern et al 2012). We showed in this paper that the W1-W2 colours of a significant fraction of such objects remain very red out to large ($> 5$ kpc) radii, suggesting that a significant fraction of the mid-IR emission may arise from an extended distribution of dust in the galaxy heated by collisions with electrons from surrounding hot halo gas, rather than from a central, parsec-scale torus. We include an additional radio-loud criterion to increase the likelihood that the sample contains a high proportion of galactic nuclei with black holes that are currently accreting. In other words, our goal is to maximize the purity of the AGN sample with the data at hand.

The danger with the procedure adopted in Paper I with respect to past mid-IR selection procedures, is that such an AGN sample is not complete. This may occur, for example, if the emission comes from a jet that is variable over timescales that are short compared to the lifetime of the torus. Figure 17 compares some of the key properties of the full mid-IR excess sample and the sample with the additional cut on radio luminosity. Mid-IR excess galaxies are identified as outliers in SFR/$M_*$ versus $D_n(4000)$ space for galaxies with log SFR/$M_*$ > −11 and in Hα versus $D_n(4000)$ space for galaxies with lower specific star formation rates. We bin up the two planes in intervals of 0.15 in $D_n(4000)$, 0.25 dex in log SFR/$M_*$ and 0.1 in Hα and calculate the distribution...
Figure 15. A compilation of SDSS cut-out images of the mid-IR excess AGN in our sample with the highest [OIII] luminosities ($>10^8L_\odot$).

of W1-W2 colours in each bin. Outliers or mid-IR excess galaxies are defined to have colours that lie above the upper 95th percentile point of the distribution. In Figure 17, we plot galaxy properties as a function of the quantity $\Delta$(W1-W2), the difference between the measured W1-W2 colour of the galaxy and the colour that delineates the upper 95th percentile cut.

In the top left panel, we plot the fraction of galaxies as a function of $\Delta$(W1-W2) for the mid-IR excess sample without the radio-loud cut (black histogram) compared to the fiducial sample (black triangles). As can be seen, the sample with the radio loud cut includes a much more pronounced tail of objects with large $\Delta$(W1-W2), i.e. with mid-IR colours that are very far from the stellar locus. This supports our claim that the radio selection is increasing the purity of the AGN sample.

In the next three panels, trends in stellar mass of the host galaxy, [OIII] line luminosity and ionization parameter $\text{[OIII]}/\text{[OII]}$ are shown as a function of $\Delta$(W1-W2) for the two samples. As can be seen, [OIII] luminosity and ionization parameter increase for systems with larger W1-W2 colours in a similar manner for both classes of object. This implies that the main effect of the radio selection is to boost the fraction of galaxies with the most extreme W1-W2 colours, which are also the most optically luminous systems with the highest ionization parameters. More detailed studies using spatially resolved data will be necessary to figure out the physical nature of the central radio emission (jet or central starburst) and whether or not the radio source is influencing
the structure of the dust emission in the central regions of the galaxy.

7 SUMMARY

We now summarize the main results of our analysis. We have studied the narrow emission line properties and stellar populations of a sample of 1385 radio-detected, mid-IR excess AGN in order to understand the physical conditions in the interstellar medium of these objects. We compare these systems with a control sample of 50,000 AGN selected by their optical emission line ratios that do not have a significant mid-IR excess. Our main conclusions are the following:

• The mid-IR excess AGN populate the high ionization branches of the [OIII]/Hβ versus [OI]/Hα/[SII]/Hα BPT diagrams, whereas the control sample AGN cluster near the star-forming locus and have lower ionization parameters on average.
• The mid-IR excess AGN have [OIII] luminosities that are an order of magnitude large on average than the control sample AGN.
• The mid-IR excess AGN have higher electron densities, but similar metal abundances to the control sample.
• The HδA versus Dn(4000) diagrams show that a much larger fraction of the host galaxies of mid-IR excess AGN have experienced recent bursts of star formation. These recent starburst galaxies have lower stellar metallicities and higher Mg/Fe ratios.
• The number densities of mid-IR excess AGN are a 1000 times smaller than those of control sample AGN at low [OIII] luminosities (∼10^6L_⊙), but at the very highest [OIII] lumi-
nosities probed by our sample (∼10^9L_⊙), mid-IR excess AGN become more populous by a factor of 10.

- Mid-IR excess AGN contribute about half the total present-day black hole growth in galaxies with stellar masses larger than 10^{11}M_⊙, whereas control sample AGN are currently the dominant contributor in lower mass systems.

It is well known that the AGN population evolves strongly to higher luminosities at higher redshifts, and it is likely that AGN similar to the mid-IR excess population studied in this paper become much more populous. We note that more than 95% of all AGN in the parent sample with [OIII] luminosities greater than 10^8L_⊙ are included in the mid-IR excess/radio sample studied in this paper, suggesting that the two selection techniques converge at the highest luminosities.

The future usefulness of our low redshift sample will lie in spatially resolved spectroscopic follow-up studies of various kinds, as in the Harrison et al study of the teacup AGN. These studies are required in order to understand how accretion onto the central supermassive black hole is occurring, the physical origin and location of the very high ionization gas in these systems, and the impact of the energetic processes occurring near the black hole on the interstellar medium of the host galaxy. The establishment of a technique that selects a population of AGN seen at different phases along a starburst cycle is also interesting for more detailed follow-up programs. Although ‘AGN feedback’ in the form of extended outflowing gas is now established in a variety of AGN sub-populations such as the most luminous Type II quasars and radio galaxies, understanding the global ubiquity, energetics and duty cycle of the feedback will require more carefully controlled statistical approaches.

Finally, our sample is an interesting one for understanding the relation between AGN activity, galaxy-galaxy interactions, mergers between black holes, and the origin of powerful AGN driven outflows of gas. It is rather interesting that although the number densities of IR excess and control sample AGN are very different, the integrated [OIII] emissivity in both classes of objects peaks at a stellar mass of ∼10^{10.5}M_⊙. We note that this was shown for the AGN population as a whole in Heckman & Kauffmann (2004, see their Figure 4). This value (10^{10.5}M_⊙) corresponds closely to the transition mass where the galaxy population switches over from a blue, star-forming, disk-dominated population to a red, passive, bulge-dominated one. Energetic feedback from AGN has been hypothesized to cause this transition, but considerable uncertainty remains as to how this occurs in practice. Some models assume that a feedback mode associated with radio galaxies accreting hot gas at the centers of massive dark matter halos is responsible for this transition (Croton et al 2006), while others invoke quasar-driven feedback triggered by galaxy-galaxy mergers (Hopkins et al 2006). Identification of a population of very luminous AGN clearly associated with galaxy-galaxy mergers is the first step to answering this question empirically.

ACKNOWLEDGMENTS

I thank Patricia Sanchez-Blazquez and Tim Heckman for helpful discussions and Mazda Adli for his support.

REFERENCES

Abazajian K. N., et al., 2009, ApJS, 182, 543-558
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Balogh M. L., Morris S. L., Yee H. K. C., Carlberg R. G., Ellingson E., 1999, ApJ, 527, 54
Belfiore F., et al., 2016, MNRAS, 461, 3111
Best P. N., Kauffmann G., Heckman T. M., Ivezić Z., 2005, MNRAS, 362, 9
Best P., 2005, HiA, 13, 329
Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Buchanan C. L., McGregor P. J., Bicknell G. V., Dopita M. A., 2006, AJ, 132, 27
Capetti A., Baldi R. D., 2011, A&A, 529, A126
Cisternas M., et al., 2011, ApJ, 726, 57
Condon J. J., Huang Z.-P., Yin Q. F., Thuan T. X., 1991, ApJ, 378, 65
Croton D. J., et al., 2006, MNRAS, 365, 11
Properties of AGN selected by mid-IR Colours

Dopita M. A., Groves B. A., Sutherland R. S., Binette L., Cecil G., 2002, ApJ, 572, 753
Drake C. L., McGregor P. J., Dopita M. A., van Breugel W. J. M., 2003, AJ, 126, 2237
Fan X., et al., 2001, AJ, 122, 2833
Ferguson J. W., Korista K. T., Baldwin J. A., Ferland G. J., 1997, ApJ, 487, 122
Gelderman R., Whittle M., 1994, ApJS, 91, 491
Groves B. A., Dopita M. A., Sutherland R. S., 2004a, ApJS, 153, 75
Groves B. A., Dopita M. A., Sutherland R. S., 2004b, ApJS, 153, 9
Harrison C. M., Thomson A. P., Alexander D. M., Bauer F. E., Edge A. C., Hogan M. T., Mullaney J. R., Swinbank A. M., 2015, ApJ, 800, 45
Heckman T. M., Kauffmann G., Brinchmann J., Charlot S., Tremonti C., White S. D. M., 2004, ApJ, 613, 109
Ho L. C., 2008, ARA&A, 46, 475
Holt J., Tadhunter C. N., Morganti R., 2009, MNRAS, 400, 589
Hopkins P. F., Hernquist L., Cox T. J., Di Matteo T., Robertson B., Springel V., 2006, ApJS, 163, 1
Kauffmann G., et al., 2003a, MNRAS, 341, 33
Kauffmann G., et al., 2003b, MNRAS, 346, 1055
Kauffmann G., 2014, MNRAS, 441, 2717
Kauffmann G., 2018, MNRAS, 473, 5210 (Paper I)
Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Trevena J., 2001, ApJ, 556, 121
Kewley L. J., Groves B., Kauffmann G., Heckman T., 2006, MNRAS, 372, 961
Levesque E. M., Richardson M. L. A., 2014, ApJ, 780, 100
Li C., Kauffmann G., Heckman T. M., White S. D. M., Jing Y. P., 2008, MNRAS, 385, 1915
Liu G., Zakamska N. L., Greene J. E., Nesvadba N. P. H., Liu X., 2013, MNRAS, 436, 2576
Liu G., Zakamska N. L., Greene J. E., Nesvadba N. P. H., Liu X., 2013, MNRAS, 430, 2327
Manti S., Gallerrani S., Ferrara A., Greig B., Feruglio C., 2017, MNRAS, 466, 1160
Pogge R. W., 1988, ApJ, 328, 519
Reichard T. A., Heckman T. M., Rudnick G., Brinchmann J., Kauffmann G., Wild V., 2009, ApJ, 691, 1005
Reyes R., et al., 2008, AJ, 136, 2373
Richardson C. T., Allen J. T., Baldwin J. A., Hewett P. C., Ferland G. J., 2014, MNRAS, 437, 2376
Ryde N., Schultheis M., 2015, A&A, 573, A14
Sanders D. B., Soifer B. T., Elias J. H., Madore B. F., Matthews K., Neugebauer G., Scoville N. Z., 1988, ApJ, 325, 74
Singh R., et al., 2013, A&A, 558, A43
Soltan A., 1982, MNRAS, 200, 115
Stern D., et al., 2012, ApJ, 753, 30
Thomas D., Maraston C., Bender R., 2003, MNRAS, 339, 897
Thomas D., et al., 2013, MNRAS, 431, 1383
Tremonti C. A., et al., 2004, ApJ, 613, 898
Tripicco M. J., Bell R. A., 1995, AJ, 110, 3035
Veilleux S., Osterbrock D. E., 1987, ApJS, 63, 295
Villforth C., et al., 2014, MNRAS, 439, 3342
Volonteri M., Rees M. J., 2005, ApJ, 633, 624
Volonteri M., Rees M. J., 2006, ApJ, 650, 669
Wild V., Kauffmann G., Heckman T., Charlot S., Lemson G., Brinchmann J., Reichard T., Pasquali A., 2007, MNRAS, 381, 543
Yu Q., Tremaine S., 2002, MNRAS, 335, 965
Zakamska N. L., et al., 2003, AJ, 126, 2125
Zakamska N. L., Strauss M. A., Heckman T. M., Ivezić Ž., Krolik J. H., 2004, AJ, 128, 1002
Zakamska N. L., et al., 2006, AJ, 132, 1496