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The Overdense Environments of *WISE*-Selected, Ultra-Luminous, High-Redshift AGN in the Submillimeter

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The environments around *WISE*-selected hot dust obscured galaxies (Hot DOGs) and *WISE*/radio-selected active galactic nuclei (AGNs) at average redshifts of $z = 2.7$ and $z = 1.7$, respectively, were found to have overdensities of companion Submillimeter-selected sources. The overdensities were of ∼2–3 and ∼5–6 , respectively, compared with blank field submm surveys. The space densities in both samples were found to be overdense compared to normal star-forming galaxies and Submillimeter galaxies (SMGs). All of the companion sources have consistent mid-IR colors and mid-IR to submm ratios to SMGs. Monte Carlo simulations show no angular correlation, which could indicate protoclusters on scales larger than the SCUBA-2 1.5 arcmin scale maps. *WISE*-selected AGNs appear to be good indicators of overdense areas of active galaxies at high redshift.

Keywords: galaxies: active, galaxies: clusters: general, galaxies: high-redshift, galaxies: quasars: general, infrared: galaxies, submillimeter: galaxies

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1. INTRODUCTION

There has been previous evidence of overdense regions around high-redshift luminous galaxies (Blain et al., 2004; Borys et al., 2004; Farrah et al., 2006; Scott et al., 2006; Gilli et al., 2007; Magliocchetti and Brüggen, 2007; Chapman et al., 2009; Hickox et al., 2009; Cooray et al., 2010; Hickox et al., 2012; Donoso et al., 2014; Umehata et al., 2014). The evolution and properties of active galactic nuclei (AGNs) are connected to their host galaxies properties and their environments. The environments around high-redshift radio galaxies (HzRGs) and radio loud AGNs (RLAGNs)[1] have also been found to be overdense in dusty companions (Stevens et al., 2003; De Breuck et al., 2004; Falder et al., 2010; Galametz et al., 2010, 2012; Stevens et al., 2010; Mayo et al., 2012; Wylezalek et al., 2013; Dannerbauer et al., 2014; Hatch et al., 2014; Rigby et al., 2014; Wylezalek et al., 2014). RLAGNs are mostly found in giant, massive, elliptical galaxies and are in very dense environments (Matthews et al., 1964; Best et al., 2005; Donoso et al., 2010; Wylezalek et al., 2013). These could be signposts of high-redshift galaxy clusters (Wylezalek et al., 2013; Hatch et al., 2014).

Overdense environments around AGNs could be evidence for massive dark matter halos and highlight the bias of this distribution as compared with the underlying dark matter distribution. It is important to understand the evolution of the underlying dark matter distribution because the formation of dark matter halos are connected to the formation of galaxies and therefore to the

[1] RLAGNs can be classified by $S_{5GHz} / S_B \geq 10$ (Kellermann et al., 1989; Miller and Goodrich, 1990; Urry and Padovani, 1995) and $L_{500\,MHz} \geq 10^{27.5}$ W Hz^{-1} (Donoso et al., 2010; Hatch et al., 2014).

properties of galaxies in the local Universe (Mo and White, 2002; Wechsler et al., 2006; Bett et al., 2007; Gao et al., 2007; Jing et al., 2007; Wetzel et al., 2007; Fakhouri and Ma, 2009; Fakhouri et al., 2010; Faltenbacher and White, 2010; Wake et al., 2012; Avila et al., 2014). Studying galaxies at higher redshifts can reveal the processes that have formed galaxies around us today.

The question of why AGN lie in dense regions and how they are affected by their environments is still debated. One suggestions is that there is hot halo mode accretion (cooling of the hot viralised atmospheres) in dense environments and cold mode accretion (galaxies accrete gas directly from cold dense intergalactic filaments) in less dense environments (Coil et al., 2009; Fanidakis et al., 2011). Coldwell and Lambas (2006) concluded that the number density of galaxies around AGN is similar to that around normal galaxies. Likewise Miller et al. (2003) found no difference in the local density around field galaxies and AGN. This is in contrast to results from for example, Kauffmann et al. (2004), Ruderman and Ebeling (2005), Serber et al. (2006), and Georgakakis et al. (2007) that indicate higher galaxy density around AGN. Quasars ($M_i \leq -22$, $z \leq 0.4$) have been found to have high density regions around them at radii between 25 kpc and 1 Mpc, with the overdensity being greatest closest to the quasar (Serber et al., 2006). Hatch et al. (2011) also found overdense regions surround Hα emitters at $z \sim 2$ that could be signposts to protocluster environments. They concluded that galaxy growth was accelerated in dense environments in the early Universe. Simulations have shown small-scale excess at scales below $\sim$100 h^{-1} kpc (Degraf et al., 2011), consistent with observational evidence (Hennawi et al., 2006; Myers et al., 2007).

The clustering of galaxies is important because it signposts the environment richness of the galaxies. Galaxies reside in dark matter halos and the mass of the dark matter halos determines the clustering strength and the strength of the biasing (Strauss and Willick, 1995). Clustering can be used to measure dark matter halo mass and how the galaxies populate the dark matter halos (Coil, 2013), and constrain cosmological parameters in galaxy evolution models for example baryon density (Davis et al., 1985; Kauffmann et al., 1993; Navarro et al., 1996; Springel et al., 2005; Coil, 2013).

Studying the environments of Hot DOGs and *WISE*/radio AGNs will help to understand the evolution of galaxies and the link with their host galaxy.

2. SAMPLES

Advances in infrared (IR) telescope technology like the NASA's *Wide-Field Infrared Survey Explorer* (*WISE*; Wright et al., 2010) have enabled observations of luminous AGN that have been difficult to find with previous IR missions. *WISE* is able to find luminous, dusty, high-redshift, active galaxies because the hot dust heated by AGN and/or starburst activity can be traced using the *WISE* 12 μm (W3) and 22 μm (W4) bands. Eisenhardt et al. (2012), Bridge et al. (2013), and Lonsdale et al. (2015) have shown that *WISE* can find different classes of interesting, luminous, high-redshift, dust-obscured AGN.

Submillimeter observations using the James Clerk Maxwell Telescope (JCMT) Submillimeter Common-User Bolometer Array 2 (SCUBA-2) (Holland et al., 2013) of two subsamples of *Wide-Field Infrared Survey Explorer* (*WISE*; Wright et al., 2010) selected galaxies found overdensities of Submillimeter galaxies (SMGs)[2] (Jones et al., 2014, 2015).

The first subsample of *WISE*-selected galaxies were faint or undetectable flux densities in the 3.4 μm (W1) and 4.6 μm (W2) bands, and well detected fluxes in the W3 and/or W4 bands, with a radio blind selection, giving a "W1W2-dropout" selection yielding hot, dust obscured galaxies (Hot DOGs) (Eisenhardt et al., 2012; Wu et al., 2012).

The second subsample were found by Lonsdale et al. (2015), by combining *WISE* and National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS) (Condon et al., 1998) and/or Faint Images of the Radio Sky at Twenty-cm (FIRST) (Becker et al., 1995). They were selected in a similar method in the mid-IR, and are a similarly high luminosity, dust-obscured population and in this paper are known as *WISE*/radio AGNs. The strong compact radio emission could be from AGN jets (Lonsdale et al., 2015).

3. OVERDENSITY

JCMT SCUBA-2 observations of all the *WISE*-selected AGN were in the "CV DAISY" mode that produces a uniformly deep coverage 3-arcmin diameter map (Holland et al., 2013). Seventeen companion sources were detected at 3 σ significance or above in 10 JCMT SCUBA-2 fields of Hot DOGs reported by Jones et al. (2014) with an average root mean square (RMS) noise of 1.8 mJy beam^{-1}. Comparing these number counts to "blank field submm" surveys shows them to be overdense, with overdensity factor of 2–3, Jones et al. (2015).

Eighty-one companion sources were detected at 3 σ or greater significance in 30 *WISE*/radio-selected AGN fields reported by Jones et al. (2015) with average RMS noise of 2.1 mJy beam^{-1}. Comparing these number counts to "blank field submm" surveys shows them to be overdense, with overdensity factor of 5–6, Jones et al. (2014). The typical redshift of the 10 observed Hot DOGs is $z = 2.7$ (Jones et al., 2014).

WISE/radio-selected AGN were found to have a higher density of SMGs when compared with Hot DOGs by a factor of 2.4 $\pm$ 0.9 (Jones et al., 2015). The *WISE*/radio AGNs have a lower redshift range, fewer of the *WISE*-selected AGNs are submm detected and lower total IR luminosities compared with Hot DOGs (Jones et al., 2014, 2015). The K-correction at wavelengths longer than 500 μm remains approx. constant with increasing redshift. Due to this K-correction effect the SCUBA-2 fraction of SMG detection should be independent of redshift.

[2]Submm galaxies (SMGs) were historically defined by having a submm flux density of $S_{850\,\mu m} > 2$ mJy. SMGs are massive gas-rich, high-redshift galaxies with high IR luminosities, $L_{IR} \geq 10^{12}$ $L_{\odot}$, believed to be from starburst activity, with star formation rates (SFRs) of several 100–1,000 $M_{\odot}$ yr^{-1} (Smail et al., 1997; Ivison et al., 1998; Eales et al., 1999; Smail et al., 2000; Blain et al., 2002; Pope et al., 2006; Casey et al., 2014; Swinbank et al., 2014). SMGs are enshrouded by dust and hence are faint in optical and near-IR wavelengths.

The typical redshift of *WISE*/radio AGNs, $z = 1.3$ (Jones et al., 2015).

4. PROPERTIES OF COMPANION SOURCES

The average submm flux density of SMGs around Hot DOGs is $S_{850\,\mu m} = 6.2 \pm 1.8$ mJy, which is comparable to SMGs around *WISE*/radio AGNs, $S_{850\,\mu m} = 7.2 \pm 2.1$ mJy. Submm flux densities provide a reliable measurement of SFR (Alexander et al., 2016). The average SFR is $\simeq$1,240 $M_\odot yr^{-1}$ for SMGs around *WISE*/radio AGNs, slightly lower than the SFR $\simeq$1,460 $M_\odot yr^{-1}$ for SMGs around Hot DOGs.

The star formation rate density (SFRD) represents the total star formation transpiring per unit time and volume at a given redshift. The SFRDs range for Hot DOGs from 1,523 $\pm$ 30$M_\odot$ yr^{-1} Mpc^{-3} to 7,949 $\pm$ 159 $M_\odot$ yr^{-1} Mpc^{-3}, and average 3,533 $M_\odot$ yr^{-1} Mpc^{-3}. These are lower than *WISE*/radio AGNs with a range from 1,219 $\pm$ 49 $M_\odot$ yr^{-1} Mpc^{-3} to 18,715 $\pm$ 374 $M_\odot$ yr^{-1} Mpc^{-3}, and average 3,929 $M_\odot$ yr^{-1} Mpc^{-3}. These values are consistent to four *Herschel* Multitiered Extragalactic Survey (HerMES) clusters of dusty, star-forming galaxies at redshifts between $z = 0.76$ to $z = 2.26$, and other clusters with MIR/FIR measurements from the literature with SFRDs ranging from $\sim$200$M_\odot$ yr^{-1} Mpc^{-3} to $\sim$3,000$M_\odot$ yr^{-1} Mpc^{-3}.

No counterparts to the companion sources from point sources were found in the third *XMM-Newton* companion Source Catalog, *3XMM*-DR5 (Rosen et al., 2015). None of the companion sources around Hot DOGs or *WISE*/radio AGNs were detected at radio wavelengths in FIRST and/or NVSS, where the typical 1.4 GHz detection limit was 1.0 mJy/beam.

Both sets of companion sources have similar *WISE* colors, Jones et al. (2017). When comparing with the *WISE* color-color diagram of different galaxy populations in Figure 12 in Wright et al. (2010) and Figure 26 in Jarrett et al. (2011), the companion sources lie in both the starburst (star-forming) galaxy zone and AGN zone.

The Hot DOGs and *WISE*/radio AGNs are redder than the companion sources, due to the *WISE*-selected AGN having higher dust obscuration and/or a higher AGN contribution, and higher dust temperatures than that of their companion sources. Hot DOGs and *WISE*/radio AGNs are predominantly powered by AGN (Wu et al., 2012; Jones et al., 2014, 2015; Lonsdale et al., 2015; Tsai et al., 2015). SMGs are predominantly powered by star formation (Alexander et al., 2005), with cooler dust emission (20–50 K) (Hainline et al., 2009).

5. CLUSTERING

The angular two-point correlation function $\omega(\theta)$ is a statistical way to determine the clustering of galaxies in 2D space (Efstathiou et al., 1991; Connolly et al., 1998), using the angular version of the 3D spatial correlation function (Peebles, 1980). It is the excess probability of finding galaxies separated by θ above the probability with a random distribution. The popular estimators described by Landy and Szalay (1993) was used, see **Figure 1**.

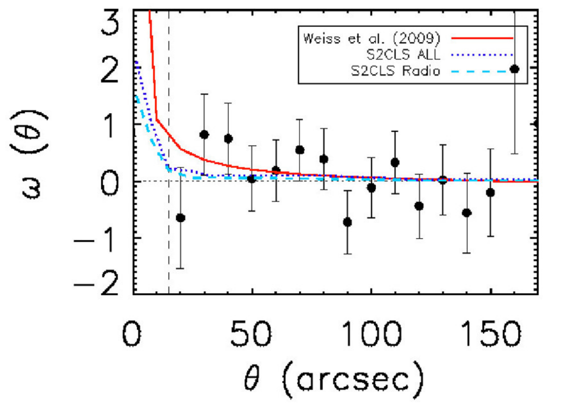

FIGURE 1 | Observed angular two-point correlation function using the Landy and Szalay (1993) equation, from Jones et al. (2017). The red solid curve shows the observed angular two-point correlation function for Weiß et al. (2009). The blue dotted line and cyan dashed line show the observed angular two-point correlation function for all the SMGs and the subset of radio-detected SMGs, respectively, in the S2CLS (Wilkinson et al., 2017). Black points represent the observed angular two-point correlation function for the companion sources detected around *WISE*/radio AGNs. The dashed line represents the JCMT SCUBA-2 850 µm beam size (15 arc s). There were not enough data for reliable and accurate results using the Hot DOGs.

The two-point angular clustering signal provided an upper limit to the strength of angular clustering (Jones et al., 2017), see **Figure 1**. Monte Carlo simulations showed no angular correlation, which could indicate protoclusters on scales larger than the SCUBA-2 1.5 arcmin scale maps.

Muldrew et al. (2015) investigated protoclusters and their environments using the Millennium Simulation. They found that protocluster structures are very extended at redshifts $z = 2$, with 90% of their mass is dispersed across $\sim$30 arcmin ($\sim$35 h^{-1} Mpc comoving). This suggests that many observations of protoclusters and high-redshift clusters are not imaging the full cluster. This could explain why there is an upper limit of angular clustering in the Hot DOGs and *WISE*/radio AGNs fields on $\sim$1.5 arcmin scales. Alternatively, the cluster might be peaked substantially off-center from the *WISE* target. Further and wider observations of companion sources in the fields around *WISE*/radio AGN are needed to determine the clustering of *WISE*-selected AGN.

6. DISCUSSION/CONCLUSION

1. Hot DOGs and *WISE*/radio AGNs have very high total IR luminosities, hot dust temperatures (60–120 K), and SEDs that are not well fitted by many standard AGN templates due to excess mid-IR emission and less submm emission (Jones et al., 2014, 2015).

2. Hot DOGs and *WISE*/radio AGNs appear to be consistent with the same population of very luminous, AGN-dominated galaxies but are different redshifts. They could be a new transient phase of the major merger model (Jones et al., 2014, 2015).

3. *WISE*/radio AGNs are typically at a lower redshift ($z = 1.7$) than Hot DOGs ($z = 2.7$). The lower redshift *WISE*/radio AGNs appear to reside in higher density regions compared with higher redshift Hot DOGs. This could be due to differences in redshift and/or radio emission. However, more observations are needed because only 10 targets in each sample have known redshifts, Jones et al. (2017).

4. The space densities of SMGs around the *WISE*-selected AGNs were found to overdense compared to normal star-forming galaxies and SMGs in the S2CLS, Jones et al. (2017).

5. There is an upper limit to the strength of angular clustering of the companion SMG sources in Hot DOGs and *WISE*/radio AGNs on SCUBA-2 1.5 arcmin scales. The typical separations when compared to Monte Carlo simulations showed no angular clustering. This is an agreement with the cumulative fraction of companion sources in different radii from the *WISE* target. This could be because they are satellite galaxies in the massive halo or that the protocluster is on bigger scales (up to ~ 30 arcmin) and we are not fully probing the protocluster, Jones et al. (2017).

6. The SMGs around *WISE*/radio AGNs $\sim 18\%$ higher SFRs than SMGs around Hot DOGs, Jones et al. (2017).

7. The SFRDs of the *WISE*-selected AGNs are higher than field galaxies, and consistent with values for known clusters of dusty galaxies, Jones et al. (2017).

8. The companion sources detected around Hot DOGs and *WISE*/radio AGNs have *WISE* colors consistent with star-forming galaxies and mid-IR to submm ratios not consistent with AGN dominated sources. This could imply that they are all consistent with SMGs, Jones et al. (2017).

9. All the companion sources have bluer mid-IR positions in the *WISE* color-color plot compared with Hot DOGs and *WISE*/radio AGNs, which implies cooler dust temperatures than 60–120 K, Jones et al. (2017).

10. Hot DOGs and *WISE*/radio AGNs appear to be good indicators of overdense environments of active galaxies in arcmin scales, Jones et al. (2017).

11. Further spectroscopic redshift data of the *WISE*-selected targets and their companion SMG sources are needed.

12. Further submm data of *WISE*-selected targets are needed to increase the sample size of *WISE*-selected targets. Also high-resolution ALMA data are needed to resolve the galaxies to see if there are multiple components for example of *WISE*-selected Hot DOG W2026+0716.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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