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# Galaxy pairs in the Sloan Digital Sky Survey – XII. The fuelling mechanism of low-excitation radio-loud AGN

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## ABSTRACT

We investigate whether the fuelling of low-excitation radio galaxies (LERGs) is linked to major galaxy interactions. Our study utilizes a sample of 10 800 spectroscopic galaxy pairs and 97 post-mergers selected from the Sloan Digital Sky Survey with matches to multiwavelength data sets. The LERG fraction amongst interacting galaxies is a factor of 3.5 higher than that of a control sample matched in local galaxy density, redshift and stellar mass. However, the LERG excess in pairs does not depend on projected separation and remains elevated out to at least 500 $h_{70}^{-1}$ kpc, suggesting that major mergers are not their main fuelling channel. In order to identify the primary fuelling mechanism of LERGs, we compile samples of control galaxies that are matched in various host galaxy and environmental properties. The LERG excess is reduced, but not completely removed, when halo mass or $D_{4000}$ are included in the matching parameters. However, when *both* $M_{\rm halo}$ and $D_{4000}$ are matched, there is no LERG excess and the 1.4 GHz luminosities (which trace jet mechanical power) are consistent between the pairs and control. In contrast, the excess of optical and mid-IR selected active galactic nuclei (AGN) in galaxy pairs is unchanged when the additional matching parameters are implemented. Our results suggest that whilst major interactions may trigger optically and mid-IR selected AGN, the gas which fuels the LERGs has two secular origins: one associated with the large-scale environment, such as accretion from the surrounding medium or minor mergers, plus an internal stellar mechanism, such as winds from evolved stars.

**Key words:** galaxies: active – galaxies: interactions – galaxies: Seyfert – radio continuum: galaxies.

## 1 INTRODUCTION

The accretion of gas on to a central supermassive black hole results in the emission of energy over a range of wavelengths, leading to a variety of available techniques for the identification of active galactic nuclei (AGN). Compton up-scattering of UV photons within the accretion disc leads to X-ray emission, heating of the dust torus is manifest in the mid-infrared (mid-IR), broad and/or narrow optical emission lines may be observed depending on viewing angle and powerful radio jets emit through synchrotron radiation. Whilst many of these AGN identifiers are complementary, and different techniques can, in theory, detect a given AGN, there are also important distinctions between AGN classes. Importantly, the emerging picture over the last decade is that AGN can accrete their material in at least two modes (e.g. Best et al. 2005; Tasse et al. 2008; Hickox et al. 2009; Trump et al. 2011; Best & Heckman 2012; Janssen et al. 2012; Gurkan, Hardcastle & Jarvis 2014). The first, commonly called 'quasar', 'radiative' or 'high-excitation' mode, refers to AGN with fairly high accretion rates, in which the material is accreted from an optically thick, geometrically thin disc. Such AGN emit their energy across a broad spectral range, including through optical emission lines, IR radiation from the heated dust torus, and, in some cases, radio jets. The host galaxies of radiatively efficient AGN tend to be actively star forming, harbour relatively low-mass black holes and have small stellar bulges (Kauffmann et al. 2003; Best et al. 2005; Smolcic 2009; Best & Heckman 2012). However, there may be a minimum value to the accretion rate that is required in order to yield such radiatively efficient AGN (e.g. Narayan & Yi 1995; Trump et al. 2011). The second type of AGN is therefore radiatively inefficient (or 'low excitation'); these AGN are thought to be fuelled by cooling, advection dominated accretion flows, or through Bondi accretion, emitting most of their energy in the form of radio jets, with a characteristic lack of X-ray, optical line and mid-IR emission (Hine & Longair 1979; Jackson & Rawlings 1997; Hardcastle, Evans & Croston 2006). The accretion rates of radiatively inefficient AGN are typically much lower than the high-excitation AGN and have high-mass black holes, low rates

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of star formation and more massive stellar bulges (Best et al. 2005; Tasse et al. 2008; Kauffmann & Heckman 2009; Best & Heckman 2012). Therefore, whilst AGN identified at X-ray, mid-IR or optical wavelengths are generally members of the 'high-excitation' family, radio-loud AGN may be either high-excitation, or low-excitation radio galaxies (HERGs and LERGs, respectively). The distinction of the HERGs and the LERGs amongst radio-loud AGN therefore epitomizes the paradigm of the two fuelling modes of AGN accretion (Best et al. 2005; Hardcastle, Evans & Croston 2007; Best & Heckman 2012).

Underlying the existence of the two AGN accretion modes is the fundamental question of what physical mechanisms are responsible for the delivery of gas to the galactic centre, and whence this gas originates. It has been suggested that high-excitation (radiatively efficient) AGN require a plentiful supply of cold gas, such as could be supplied during a merger (e.g. Johansson, Naab & Burkert 2009; Kauffmann & Heckman 2009; Capelo et al. 2015). Indeed, there are now many studies that have shown that interactions over a wide range of mass ratios *can*[1] trigger AGN that are selected variously in the optical (e.g. Alonso et al. 2007; Ellison et al. 2011, 2013; Kaviraj 2014; Khabiboulline et al. 2014), mid-IR (Satyapal et al. 2014; Shao et al. 2015) and X-ray (Koss et al. 2010, 2012; Silverman et al. 2011; Lackner et al. 2014). For radio-selected AGN, there is evidence to support a connection between mergers and both HERGs and the highest luminosity radio-loud AGN (e.g. Ramos-Almeida et al. 2011; Tadhunter et al. 2011; Kaviraj et al. 2015).

In contrast to the radiatively efficient AGN, theoretical models, and their comparison to observations, indicate that the radiatively inefficient accretion that leads to LERGs need not be interaction-induced, and can be maintained through low level accretion from hot gas in galactic haloes, either through a Bondi-like process, or through cooling (Best et al. 2005, 2006; Allen et al. 2006; Hardcastle et al. 2007; Gaspari, Ruszkowski & Oh 2013). Indeed, elliptical galaxies are known to be surrounded by large reservoirs of hot gas, created by mass-loss from evolved stellar populations and fed from external reservoirs such as the intergalactic and intracluster media (IGM and ICM, respectively, see Mathews & Brighenti 2003 for a review) or through minor mergers. The dependence of LERG prevalence on environment indicates that some of the gas that fuels the AGN may indeed originate in the IGM or ICM (e.g. Best et al. 2007).

Although the picture of stochastic, low accretion rates in LERGs is generally considered to operate independently of mergers, several recent works have presented observations that indicate that interactions *do* contribute to the fuelling of LERGs. For example, Sabater, Best & Argudo-Fernandez (2013) found that the fraction of LERGs is enhanced by interactions, as inferred through a tidal force indicator. The LERG excess is detected even when the stellar mass of the galaxy (correlated with the galactic halo mass, and hence an indirect measure of the hot halo reservoir) is accounted for. Pace & Salim (2014) find an excess of close companions (within 100 kpc) around LERGs compared to radio-quiet galaxies. The excess of satellites persists even when cluster membership is controlled for, indicating that the availability of hot gas (either internal or external) is not the only requirement for producing a LERG. These and other works (e.g. Tasse et al. 2008) have concluded that interactions with near neighbours may contribute to the fuelling of LERGs. In this paper, we aim to further test whether major interactions, between approximately equal mass galaxies, play a role in the fuelling of LERGs, as they apparently do for the high-excitation AGN selected in the optical, mid-IR and X-ray.

## 2 SAMPLES AND DERIVED PROPERTIES

The samples of galaxy pairs and post-mergers used in this work have been described fully in the previous papers in this series. We provide here brief details and refer the reader to our earlier work for more information on parent samples, effects of mass ratio, bias due to fibre collisions and morphological classifications (e.g. Ellison et al. 2008, 2010; Scudder et al. 2012; Patton et al. 2013).

We adopt the sample of spectroscopically identified pairs presented in Ellison et al. (2013). In brief, the pairs are selected from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) Main Galaxy Sample ($14.0 \leq m_r \leq 17.77$) with a redshift range $0.01 \leq z \leq 0.2$ and SDSS spec class=2. The pairs are required to have a projected separation $r_p \leq 80\ h_{70}^{-1}$ kpc, a velocity difference $\Delta V \leq 300$ km s$^{-1}$ and a stellar mass ratio within a factor of 4 of one another.[2] After rejecting 67.5 per cent of pairs with angular separations $\theta > 55$ arcsec to account for fibre collision selection effects, there are 10 800 galaxies in the pairs sample. Stellar masses, photometric properties, 4000 Å break strengths ($D_{4000}$) and total star formation rate (SFR) are taken from Mendel et al. (2014), Simard et al. (2011) and the Johns Hopkins University (JHU)/Max Planck Institut für Astrophysik (MPA) catalogues (e.g. Brinchmann et al. 2004), respectively.

In addition to the sample of close pairs, which probes the pre-coalescence phase of the merger, we also include in the analysis a sample of post-merger galaxies. The post-mergers represent visually selected galaxies that exhibit strong morphological disturbances and are likely the remnants of major mergers. The post-merger sample is described in detail in Ellison et al. (2013, 2015), in which it is shown that the post-coalescence phase corresponds to the highest SFR enhancements and AGN frequency, compared to matched control samples. After careful visual classification and the requirement of stellar mass availability (see below), there are 97 galaxies in the post-merger sample.

Three definitions of AGN are used in this work, which, for brevity, we refer to as optical, mid-IR and radio selected. Following Ellison et al. (2013), the optical AGN are selected according to the emission line criteria of Stasinska et al. (2006), which identifies galaxies with even a small contribution from AGN.[3] For the mid-IR selected AGN, we follow the work of Satyapal et al. (2014) and use a *Wide Field Infra-red Explorer* $W1-W2 > 0.5$ colour cut to select dust obscured AGN.[4] The radio-selected AGN are taken from the compilation of Best & Heckman (2012), who match the SDSS to NRAO/VLA Sky Survey (NVSS) and Faint Images of the Radio Sky at Twenty cm (FIRST) catalogues, divide radio detections into star-forming or AGN categories and use a combination of criteria to distinguish

[1] This is not to say that all radiatively efficient AGN are triggered by mergers; both observations and simulations support the likelihood that other mechanisms, such as cosmic inflows or internal instabilities could also contribute, or even dominate (Draper & Ballantyne 2012; Menci et al. 2014).

[2] Although the $\Delta V < 300$ km s$^{-1}$criterion mitigates projection effects, it is likely that not all of the pairs will result in a final merger. For example, Moreno et al. (2013) find that as few as ∼ 10 per cent of wide separation ($r_p < 250\ h_{70}^{-1}$ kpc) pairs are dominantly bound to one another.

[3] Although the exact number of AGN depends on the optical emission line threshold adopted, our results are independent of selection technique, e.g. see Ellison et al. (2011) for a comparison between optical AGN selection methods.

[4] Although $W1-W2>0.5$ is more liberal than the threshold of 0.8 that is sometimes used, its applicability at low redshift is demonstrated in Satyapal et al. (2014). Adopting a more stringent cut does not affect the conclusions of our work.

the latter into HERGs and LERGs. In this work, we select only the LERGs to constitute the sample of radio-loud AGN. The LERGs in our sample trace relatively low-luminosity AGN, with most galaxies in the range $23 < \log L_{\rm NVSS,1.4\,GHz} < 25$ W Hz$^{-1}$ (see also Best & Heckman 2012).

## 3 METHODOLOGY AND MATCHING PARAMETERS

In previous papers of this series, we have employed a matching methodology between the galaxy pairs and a control sample, in order to identify changes induced by the interaction. Our standard procedure has been to match each galaxy in a pair with a sample of control (no neighbour within 80 $h_{70}^{-1}$ kpc and 10 000 km s$^{-1}$) galaxies of the same stellar mass, redshift and local density. The latter parameter is quantified using $\Sigma_n = \frac{n}{\pi d_n^2}$, where $d_n$ is the projected distance in Mpc to the $n^{th}$ nearest neighbour within $\pm$1000 km s$^{-1}$. We adopt $n = 5$ for this work, but note that our results do not depend sensitively on the choice of $n$. Normalized densities, $\delta_5$, are computed relative to the median $\Sigma_5$ within a redshift slice $\pm$ 0.01. For each galaxy in a pair/post-merger, all possible control galaxies are identified within some specified tolerance. The tolerance for matching is 0.005 in redshift, 0.1 dex in stellar mass and 0.1 dex in normalized local density. If less than five matches are found, the tolerance is grown by a further $\Delta z = 0.005$ in redshift, $\Delta \log M_\star = 0.1$ dex in stellar mass and $\Delta\delta_5 = 0.1$ dex in normalized local density until the required number of matches is achieved. For each galaxy in a pair/post-merger, we can hence compare the average properties of its matched controls with the interaction/merger itself. Using this technique, we have previously reported trends between the projected separation of galaxy pairs and changes in SFR (Patton et al. 2013), gas-phase metallicity (Scudder et al. 2012), optical and mid-IR AGN fractions (Ellison et al. 2011, 2013; Satyapal et al. 2014) and black hole accretion rate (Ellison et al. 2013). The dependence of these quantities on projected separation is a strong indication that the interaction is responsible for changes therein.

The fuelling of the LERG AGN class has been variously suggested to be linked to the presence of close companions, accretion from the old stellar populations in the bulge, or gas accreting from the hot halo (e.g. Hopkins & Hernquist 2006; Kauffmann & Heckman 2009; Ramos-Almeida et al. 2013; Sabater et al. 2013; Karouzos et al. 2014; Pace & Salim 2014). In the latter scenario, the source of gas feeding the hot halo may either be internal (from the winds of evolved stars, or supernovae), or may be fed from the external IGM or ICM (Mathews & Brighenti 2003). In order to distinguish between these possibilities, we perform various combinations of matched parameters. Stellar mass alone is likely to be an indicator of the material in the galactic halo with an internal origin. $\delta_5$ traces local density, whilst the group halo mass (which we adopt from the DR7 catalogue originally published by Yang, Mo & van den Bosch 2009) informs us about the reservoir of gas that may be accreted from within a given dark matter halo. Stellar mass, $\delta_5$ and halo mass can therefore all be considered as tracers of environment on different scales.

In addition to environmental parameters, we consider variables that reflect the star formation properties of the galaxy. Best & Heckman (2012) have shown that LERGs are preferentially passive, lying below the star-forming main sequence. By performing a simple first-order linear least-squares fit between stellar mass and SFR for star-forming galaxies in the SDSS, and translating the fit downwards by a factor of 10 in SFR, we define the threshold between the star-forming and passive sequences. This is illustrated in Fig. 1 where the contours show all SDSS galaxies, the dashed lines show the fit to the star-forming main sequence (iclass = 1 from Brinchmann et al. 2004) and its downward translation. The points show the position of the LERGs identified by Best & Heckman (2012); as shown in that paper, the LERGs are preferentially located on the passive sequence, at relatively high stellar masses.

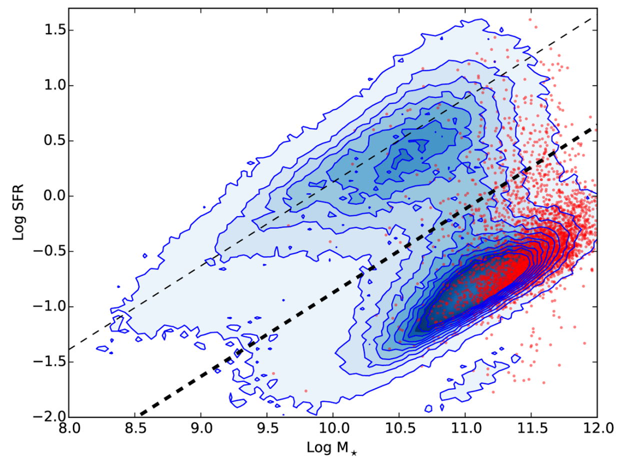


**Figure 1.** The SFRs and stellar masses of SDSS galaxies are shown as contours; two sequences are clearly visible. The star-forming sequence is fit with a first order linear least-squares fit, as shown by the light dashed line. The fit parameters are $\log {\rm SFR} = -7.4485 + \log M_\star \times 0.7575$. The heavy dashed line is translated downwards by 1 dex in log SFR at fixed stellar mass and divides our definition of the star-forming and passive sequences. Points show LERGs selected from Best & Heckman (2012).

The crudest way to match star-forming properties is to require that all controls matched to a given galaxy pair/post-merger are on the same 'sequence', i.e. either the passive, or the star-forming sequence. We can also attempt to match more precisely in SFR. However, whilst we can be fairly confident that a given galaxy is on the star-forming or passive sequence, the exact SFRs of galaxies that are quenched are quite uncertain. At least part of this uncertainty is associated with the determination of SFRs from either low S/N emission lines, or with the calibration from $D_{4000}$ (Brinchmann et al. 2004). To try to mitigate these problems, we match on the observed $D_{4000}$, rather than the inferred SFR. Matching on $D_{4000}$ is also appropriate given that we are interested in the link between the mass-loss of the old stellar population and LERG fuelling, so that the instantaneous SFR is less relevant than the integrated value traced by $D_{4000}$ (although the two properties are correlated). Finally, we investigate matching on the stellar mass of the bulge since Kauffmann & Heckman (2009) have identified a regime of black hole growth that is proportional to the bulge mass, again implicating fuelling by mass-loss from old stars.

## 4 THE FUELLING MECHANISMS OF AGN

### 4.1 LERG fractions in major galaxy mergers

In Table 1, we present a selection of combinations of matching parameters that were investigated in our quest to identify the source of gas that accretes to form LERGs. For convenience, we have labelled the sets of matching parameters that we will discuss in this work. In our previous work, our basic matching scheme has used redshift, stellar mass and $\delta_5$, which we will use as our reference parameters in this work (Set #1).

For the varying combinations of matching parameters we calculate the AGN excess, defined as the fraction of galaxies classified as AGN in the mergers (pairs or post-mergers) relative to the

**Table 1.** Average excess of LERG AGN in galaxy pairs.

| Set # | Matched parameters | Average pair LERG excess |
|---|---|---|
| 1 | $z$, $M_\star$, $\delta_5$ | $\times$ 3.5 ± 0.3 |
| 2 | $z$, $M_\star$ | $\times$ 3.8 ± 0.4 |
| 3 | $z$, $M_\star$, $\delta_5$, $M_{\rm halo}$ | $\times$ 2.0 ± 0.2 |
| 4 | $z$, $M_\star$, $\delta_5$, $M_{\rm bulge}$ | $\times$ 2.3 ± 0.2 |
| 5 | $z$, $M_\star$, $\delta_5$, sequence | $\times$ 2.8 ± 0.3 |
| 6 | $z$, $M_\star$, $\delta_5$, $D_{4000}$ | $\times$ 2.0 ± 0.2 |
| 7 | $z$, $M_\star$, $\delta_5$, $D_{4000}$, $M_{\rm halo}$ | $\times$ 1.1 ± 0.1 |
| 8 | $z$, $M_\star$, $D_{4000}$, $M_{\rm halo}$ | $\times$ 2.1 ± 0.4 |

fraction of AGN in their matched controls. We remind the reader that our sample selects likely *major* mergers, based on the mass ratio of the pairs (within 4:1) and the morphology of the post-mergers (see Ellison et al. 2013). In Fig. 2, we show the AGN excess in the optical (top panel), mid-IR (middle panel) and LERG (bottom panel) AGN for our fiducial Set # 1. The optical and mid-IR results have been previously published in Ellison et al. (2013) and Satyapal et al. (2014), but are presented here for comparison with the radio-selected LERGs. Fig. 2 shows that there is an average excess of LERGs in close pairs by a factor of 3.5, in qualitative agreement with the results of Sabater et al. (2013) and Pace & Salim (2014). The LERG excess is even higher in the post-mergers: a factor of ~8. However, unlike the optical and mid-IR AGN fractions, there is no dependence of the LERG excess on projected separation. Moreover, by using a sample of wide separation pairs (Patton et al. 2013) and adopting the control procedures described in Patton et al. (in preparation) we find that the excess of LERGs in pairs continues out to separations of at least 500 kpc. Interactions are unlikely to precipitate changes in galaxy properties over such large separations. For example, SFR enhancements in the same wide pairs sample persist only out to ~150 kpc (Patton et al. 2013). It is therefore possible that the LERG excess in the lower panel of Fig. 2 is not due to interactions, but some residual dependence of the LERG fraction on other galaxy properties.

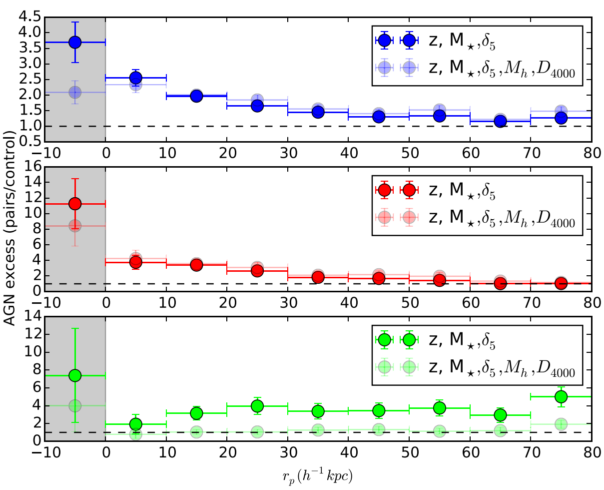


**Figure 2.** The fraction of AGN in galaxy pairs and post-mergers (grey box) relative to their matched controls (the AGN excess) as a function of projected separation. Optically selected, mid-IR selected and radio selected are shown in the top, middle and bottom panels, respectively. In all panels, the bright colours show the fiducial matching set (Table 1 Set #1) and the pale colours represent Set #7. The optical and mid-IR selected AGN show a trend of increasing AGN excess towards smaller projected separations; this trend persists even when $D_{4000}$ and halo mass are matched. Although there is an excess of LERGs (lower panel) for the fiducial matching set, there is no trend with projected separation, and the excess disappears when $D_{4000}$ and halo mass are matched.

We quantify the AGN excess for the various combinations of matching parameters listed in Table 1. We begin by considering environmental metrics, since radio-loud AGN are known to be located in preferentially overdense regions. Local density ($\delta_5$) apparently has little impact on the LERG excess, since removing it from the matching parameters (Set #2) does not significantly change the average LERG excess. Adding halo mass (matched to within a tolerance of 0.1 dex) to the fiducial matching set (Set #3) does reduce the LERG excess, but there remains a factor of 2 more LERGs in pairs than in their control. Environment on the group scale therefore seems to modulate the LERG fraction to some extent, but is apparently not fully responsible for the fuelling (consistent with the conclusions of Sabater et al. 2013; Pace & Salim 2014).

We now turn to parameters that match the properties of the stellar component of the merging galaxy itself. Adding the stellar mass of the bulge (Mendel et al. 2014, matched to within a tolerance of 0.1 dex) to our fiducial parameter set (Set #4) slightly reduces the LERG excess, but there remains 2.3 times more LERGs in pairs than their controls. As shown in Fig. 1, LERGs are preferentially located in passive galaxies; without accounting for this preference many controls (e.g. in Set # 1) will be drawn from the star-forming sequence. This will lead to an enhanced LERG excess in pairs relative to the control sample. A modest reduction in the LERG excess (relative to Set # 1) is seen when requiring that control galaxies are on the same 'sequence' (passive or star forming, Set #5) as the pairs/post-mergers. Matching on $D_{4000}$ (to within a tolerance of 0.05, Set #6) performs slightly better, reducing the LERG excess to a factor of 2. The result is unchanged if we restrict the sample to only include galaxies in which the fibre is dominated by light from the bulge (based on bulge–disc decompositions from Simard et al. 2011). Therefore, as was the case for environmental properties, matching on parameters associated with the star-forming properties of the galaxy does seem to play a role in LERG fuelling, but is not the full story.

We now add both halo mass and $D_{4000}$ to our fiducial set of matching parameters (Set #7). We are thus accounting for both internal stellar properties and large-scale environment. The results are shown in pale coloured points in Fig. 2 for optical, mid-IR and radio-selected AGN. Interestingly, the optical and mid-IR AGN excess is little affected by the additional matching, and the increasing AGN excess with decreasing projected separation persists. Only the post-mergers show a significant decrease in their AGN excess. However, in the lower panel of Fig. 2 we show that the LERGs respond very differently to the additional matching of halo mass and $D_{4000}$. There is now no significant excess of radio-loud AGN in the pairs (and a statistically insignificant excess in the post-mergers). From this we conclude that the gas that fuels the LERGs can originate from either external origins, or from stellar sources within the galaxy. Once these two factors have been controlled for, there is no evidence that major galaxy interactions provide an additional fuelling mechanism. Set #7 includes two parameters that are linked to 'environment', $\delta_5$ and halo mass, and both are apparently necessary to fully account for the LERG fuelling mechanism.[5] This is

[5] Whilst there is a broad correlation between $\delta_5$ and halo mass, a large scatter exists.

demonstrated by removing $\delta_5$ in Set #8, which yields an average pair excess of $\sim 2$. We speculate that the dual contribution from halo mass and $\delta_5$ exists because whilst the former is indicative of the total reservoir of halo material, $\delta_5$ measures the local scale distribution of this material. Alternatively, the two parameters may trace different sources of external accretion, such as minor mergers and 'smooth' IGM accretion.

We also investigate whether the mechanical energy associated with the radio jet is enhanced in the pairs, compared to the control. Following Best & Heckman (2012) we compute $L_{\rm mech} = 7.3 \times 10^{36}(L_{\rm 1.4\,GHz,\,NVSS}/10^{24}\ {\rm WHz}^{-1})^{0.70}$ W, and compare $L_{\rm mech}$ in each paired galaxy with the median $L_{\rm mech}$ of its matched controls to determine $\Delta L_{\rm mech} = \log L_{\rm mech,\,pair} - \log L_{\rm mech,\,control}$. The median $\Delta L_{\rm mech} = 0.002$, indicating that there is no significant enhancement in the jet mechanical power of LERGs in close galaxy pairs. This contrasts with the accretion luminosities derived from both optical and mid-IR selected AGN, which are enhanced in the close pairs sample (Ellison et al. 2013; Satyapal et al. 2014).

## 5 CONCLUSIONS

Based on a sample of close galaxy pairs and recently coalesced post-mergers selected from the SDSS, we have investigated the origin of nuclear fuelling in LERGs. The frequency of LERGs is a factor of 3.5 higher in the pairs and a factor of 8 higher in post-mergers than in our fiducial control sample that is matched in stellar mass, redshift and $\delta_5$. However, unlike the excess of optical and mid-IR selected AGN identified in the same sample, there is no dependence of LERG excess on pair separation, and the excess persists out to at least 500 $h_{70}^{-1}$ kpc, indicating that major interactions are not the cause of the nuclear activity. Although the LERG excess is mildly reduced when either bulge mass, $D_{4000}$ or halo mass are controlled for, LERGs are still a factor of at least 2 higher in the pairs than the control. However, when we simultaneously add both halo mass and $D_{4000}$ to the fiducial control sample parameters, the LERG excess disappears. There is also no enhancement in the average mechanical jet luminosity in the pairs, relative to the control. Our results indicate that the gas responsible for fuelling low-excitation radio-loud AGN is not supplied by major mergers, but rather has two contributing secular sources: internal stellar processes (such as winds from old stars) and external accretion, which could include both minor mergers (which are not included in our sample) and smooth accretion from the IGM.

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