HerMES: SPIRE emission from radio-selected active galactic nuclei


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1 INTRODUCTION

There is now strong evidence that powerful active galactic nuclei (AGN) can provide the fuel for star formation. To complement future targeted Herschel studies of the rare, very powerful radio-loud AGN, we examine in this work less luminous radio-loud AGN, 26.5 \( \geq \log(L_{1.4}/\text{W Hz}^{-1}) \geq 25 \), which can be found in reasonable abundance over areas of a few square degrees. We use this definition of ‘radio-loud’ AGN, based on radio luminosity density (e.g. Miller, Peacock & Mead 1990), in order to avoid making any distinction between type 1 and type 2 AGN, i.e. AGN classification based upon optical spectroscopy, where different amounts of AGN obscuration may affect the relative amount of optical emission. As we shall show, most of these sources are also ‘radio-loud’ when using the definition of Kellerman et al. (1989, 5 GHz over a B-band luminosity of >10). Star formation in these less luminous radio-loud AGN
remains poorly studied, as there has been no systematic follow-up of such sources above $z > 0.1$. Recently, the importance of radio-loud AGN in this luminosity range was demonstrated by Sahina et al. (2007) who found that 40 per cent of $z \sim 2$ ultraluminous infrared galaxies (ULIRGs) with deep silicate absorption features were radio-loud and these authors postulated that such sources are transition ‘feedback’ objects after the radio jet has turned on, but before feedback has halted black hole accretion and star formation. The SPIRE instrument (Griffin et al. 2010) on board the Herschel Space Observatory (Pilbratt et al. 2010) gives us a clear view of the far-IR/sub-mm Universe at wavelengths where many galaxies emit most of their luminosity. The Herschel Multi-tiered Extragalactic Survey (HerMES; 1 Oliver et al., in preparation) provides deep IR SPIRE data over many of the best-studied extra-galactic survey fields. Recent results from Herschel show that SPIRE-detected AGN in deep HerMES fields have far-IR colours similar to the bulk of the SPIRE population which are believed to be star formation dominated (Elbaz et al. 2010; Hatziminaoglou et al. 2010), and modelling of their spectral energy distributions (SEDs) suggests that the SPIRE emission in AGN is dominated by a star-forming component (Hatziminaoglou et al. 2010).

The work presented here uses Herschel/SPIDE observations of the Spitzer Extragalactic First Look Survey (FLS) field taken as part of the Herschel Science Demonstration Phase (SDP) in 2009 October to November. Of the fields observed in SDP, this field had the best combination of wide area, uniform radio coverage and good multiwavelength follow-up. We present our sample of moderate- and high-redshift radio-loud AGN in Section 2 and derive IR luminosities and SFRs in Section 3. We present our results in Section 4 and discuss them in Section 5. We conclude this paper in Section 6. Throughout, we use a ‘concordance’ cosmology of $\Omega_M = 1 - \Omega_\Lambda = 0.3, \Omega_\Lambda = 1$ and $H_0 = 70$ km \, s$^{-1}$ \, Mpc$^{-1}$.

2 SAMPLE

2.1 Radio sample and cross-identification

Our radio data come from the 1.4-GHz Very Large Array catalogue of Condon et al. (2003), which is complete down to 0.115 mJy (5σ). We restrict our analysis to a region of the FLS with complete optical and near-IR/mid-IR coverage, defined by 257:8 < RA < 261° and 58:6 < Dec. < 60°. These optical to mid-IR ancillary data were taken from the Infrared Array Camera (IRAC) selected, multiwavelength data fusion catalogue in the FLS (hereafter, the FLS ‘Data Fusion Catalogue’) presented by Vaccari et al. (in preparation). The Data Fusion Catalogue is a Spitzer/IRAC-selected wide-area multiwavelength catalogue covering the $\sim 60$-deg$^2$ extragalactic fields covered by Spitzer/IRAC and Multiband Imaging Photometer for Spitzer (MIPS) seven-band imaging. The main selection of the catalogue requires an IRAC 3.6- or 4.5-μm detection, since the two Spitzer channels reach about the same depth. MIPS 24-μm detections are associated with IRAC sources to improve their positional accuracy, and the MIPS 70- and 160-μm detections are confirmed by an MIPS 24-μm detection to increase their reliability.

In this paper, we use the version of the Data Fusion employed in HerMES SDP work. For the FLS field, we thus use the IRAC catalogue from Lacy et al. (2005), the MIPS 24-μm catalogue from Fadda et al. (2006), and MIPS 70- and 160-μm catalogues produced by the HerMES team using the SSC-provided software (e.g. Frayer et al. 2009). We combine the mid- and far-IR data from Spitzer with optical data (ugriz) from the Isaac Newton Telescope (Solares et al., in preparation) as well as redshift information from the literature.

The redshifts come from the Sloan Digital Sky Survey (SDSS) spectroscopy and photometry as well as dedicated follow-up of many radio and mid-IR/far-IR selected targets by several groups (e.g. Martínez-Sansigre et al. 2005; Papovich et al. 2006; Weedman et al. 2006; Lacy et al. 2007; Marleau et al. 2007; Yan et al. 2007; Sahina et al. 2008; Dasyra et al. 2009). As the photometric redshifts from the SDSS do not extend accurately above $z = 1$, higher redshift sources will be dominated by the selection criteria of these different groups. We can compare the optical magnitudes and mid-IR flux densities of the sources with and without known redshifts. We find that around 100 radio sources with known redshifts are not detected in the $z$-band, but are detected at 24 μm at brighter flux densities than most sources without redshift information. Hence, as faint $z$-band sources typically lie at higher redshifts, this observation is consistent with the specific targeting of bright 24-μm sources for spectroscopic follow-up at high redshift. We discuss how we deal with this selection in Section 4.

We cross-correlated the radio catalogue with the FLS Data Fusion Catalogue using a 2-arcsec search radius between the radio and mid-IR (3.6-μm) positions. Extended/multicomponent sources from Condon et al. (2003) were inspected by eye and five were reclassified as being two or more separate sources due to the presence of more than one optical/near-IR counterpart to individual radio components. We therefore obtained a master catalogue of 1907 radio sources of which 885 had spectroscopic or photometric redshifts from the Data Fusion Catalogue (see Table 1). We illustrate in Fig. 1 the distribution in redshift/luminosity space of the sources from the master catalogue with known redshifts. Our search radius and the sky density of the FLS Data Fusion Catalogue imply that 12/1571 (i.e. <1 per cent) of our cross-identifications are by chance.

While the redshift information for our sample is incomplete, it is only important for sources that potentially satisfy our radio luminosity selection criteria and are hence included in our radio-loud sample. However, in the subsequent sections we present the selection of our radio-loud AGN samples in two different redshift ranges, assess how complete these are by comparisons to models based on the known evolution of the high-redshift radio-loud population (see Section 2.3) and how this selection will effect our sample (see Section 4).

2.2 Radio-loud selection and sub-samples

To obtain accurate luminosities, radio spectral indices are required, so we cross-correlated the master catalogue with the 610-MHz catalogue of Garn et al. (2007) finding counterparts within 6 arcsec for 68 per cent of the master sample. We use a 6-arcsec search radius to account for the positional accuracy of the 610-MHz data. For radio sources without 610-MHz counterparts, we assumed a

<table>
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<th>Table 1. Composition of the FLS master radio catalogue. We indicate the total number of sources in the master catalogue, the number with cross-identifications in the FLS Data Fusion Catalogue and redshifts, and the number of sources with redshifts and SPIRE/250-μm detections.</th>
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<td>Total number of radio sources</td>
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<td>With FLS Data Fusion XIDs and known redshifts</td>
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<td>With SPIRE/250 μm and known redshifts</td>
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1 http://hermes.sussex.ac.uk
spectral index with a value of $\alpha = -0.75$ ($S \propto \nu^\alpha$) consistent with the mean value found for faint radio sources in general (AGN and starbursts alike; e.g. Ibar et al. 2009). We note that the sample here has a slightly steeper mean radio spectral index ($\alpha = -0.82$), but the relative limits of the 1.4-GHz and 610-MHz survey result in bias against sources with a flat spectrum at low flux densities. We select our radio-loud AGN sample with luminosity density cuts of $25 \leq \log(L_{1.4}/\text{W Hz}^{-1}) \leq 26.5$. The lower limit is chosen to ensure that our sources are genuinely radio-loud and to minimize the number of extreme star-forming galaxies (SFGs) selected. Indeed, this lower radio luminosity is equivalent to a total IR (8–1000 μm) luminosity of $\sim 3 \times 10^{11} L_\odot$ from the correlation of far-IR and radio luminosities for SFGs (Yun & Carilli 2002) and therefore an SFR of $\sim 6000 M_\odot \text{yr}^{-1}$ using the relations of Kennicutt (1998). Hence, this luminosity would be extreme for a starburst galaxy. The upper limit is imposed as radio sources with luminosities greater than this cut are rare in the volume probed in this study. We find one source with such a luminosity ($L_{1.4} \sim 10^{27.5} \text{W Hz}^{-1}$ at $z \sim 2$; see Fig. 1) which is identified as an SDSS quasi-stellar object (QSO). We consider it no further in this study, but note that this radio-loud QSO is not detected in our SPIRE observations. We also find that all our ‘radio-loud’ AGN would be classified as radio-loud by the rest-frame 5 GHz to $B$-band flux ratio according to the criteria of Kellerman et al. (1989) bar three sources in the high-redshift bin which have ratios just below the cut-off value of 10.

We then separate the luminous radio sources into moderate (0.4 < $z$ < 0.9) and high (1.2 < $z$ < 3) redshift samples with 15 and 16 sources, respectively [out of a total of 36 radio sources from the master catalogue with $25 < \log(L_{1.4}/\text{W Hz}^{-1}) < 26.5$]. We chose these two redshift bins since the redshift distribution of the luminous radio sources peaks in these ranges (see Fig. 1), and hence we should obtain the most complete sub-samples possible given the data available (see below for estimates of their completeness). We note that the general decrease in known redshifts at $z \sim 1$ seen in Fig. 1 is due to the ineffectiveness of SDSS photometric and spectroscopic redshift estimation above this redshift. Hence, all the sources in the moderate-redshift sample have redshifts from SDSS (4/15 are spectroscopic with their remainder being photometric). Sources with higher known redshifts are generally from targeted follow-up of various classes of object as well as the occasional SDSS QSO. All the redshifts in the high-redshift bin are spectroscopic and come from these various follow-up projects. Interestingly, these two redshift ranges also cover similar length cosmic epochs of about 3 Gyr each. The median radio luminosities of both sub-samples are very similar: $\log(L_{1.4}/\text{W Hz}^{-1}) = 24.9$ and 25.0 for the moderate- and high-redshift samples, respectively.

### 2.3 Completeness

In Fig. 2, we show the observed distribution of radio luminosities in each redshift sample and compare this to the modelled luminosity distributions over the same volume derived from the Square Kilometre Array (SKA) Simulated Skies (S-cubed; Wilman et al. 2008) at the radio flux density limit of the FLS (0.115 mJy). As well as the total number of sources predicted in these luminosity redshift bins, we also indicate the number of extreme SFGs (SFR > 6000 $M_\odot \text{yr}^{-1}$) predicted. The class of AGN from S-cubed which dominate this distribution is the low-luminosity radio-loud AGN (Wilman et al. 2008). The evolution of this population is taken from ‘model C’ of Willott et al. (2001) and is reasonably well constrained up to $z = 2$. We then apply a high-redshift decline in space density represented by $(1 + z)^{-2.3}$ above $z = 2.5$ as recommended in Wilman et al. (2008). There is also a small, ~6 per cent, contribution to the number of sources predicted by S-cubed of ‘radio-quiet’ AGN whose evolution is less well constrained by observation. We have

![Figure 1](http://mnras.oxfordjournals.org/)  

**Figure 1.** Redshift/radio luminosity distribution of 885/1907 radio sources in our master catalogue with known redshifts. The red symbols within the dashed rectangles indicate our moderate- and high-redshift sub-samples represented by squares and circles, respectively. Note that the sub-samples are chosen in redshift ranges where they are likely to be most complete (see Fig. 2).

![Figure 2](http://mnras.oxfordjournals.org/)  

**Figure 2.** Observed number distribution versus radio luminosity density of sources in our moderate- and high-redshift samples (black solid histograms). The dashed line represents the distribution of the total number of radio sources expected in this volume from the SKA Simulated Skies (S-cubed; Wilman et al. 2008), where the number expected to be SFGs is indicated by the dot–dashed line (none is predicted in the moderate-redshift sample). The shaded region represents a 30 per cent uncertainty in S-cubed. In comparison to S-cubed, our moderate-redshift sample is 100 per cent complete and our high-redshift sample is 14 per cent complete.
The mean SFR of the undetected sources (assuming that it scales directly with mean $S^3$).

We extracted SPIRE flux densities at the positions of all radio and 3A sources using the HerMES XID method (Roseboom et al. 2010). This approach minimizes the effect of source blending, as the SPIRE flux densities are estimated via linear inversion methods using the positions of known 24-µm counterparts with no sources close enough to them which could significantly affect the measurement of their SPIRE flux density.

We derive total (8–1000 µm) IR luminosities by fitting all the data available for the 436 radio sources across the Spitzer/IRAC+MIPS and Herschel/SPIRE bands following the method outlined in Symeonidis et al. (2009) (see Fig. 3). In all cases, we use the Spitzer/24-µm and Herschel/250-/350-/500-µm photometry although in some cases the 350- and 500-µm photometry have extremely large uncertainties due to their low signal-to-noise ratio (S/N), <3, and do not significantly affect the values of $\chi^2$ derived. This fitting method uses all the models from Siebenmorgen & Krügel (2007), which cover a wide range of SED types, and finds the best fit using standard $\chi^2$ minimization from which a total IR luminosity is calculated. Uncertainties in the IR luminosity are derived from the range of values obtained from SED fits which differ from the best fit by $\Delta \chi^2 = (\chi^2 - \chi_{\text{min}}^2) < 1$.

For reference, 24 per cent of the radio sources with unknown redshifts have significant detections in the SPIRE wavebands.
3.2 AGN contribution to the far-IR luminosity

A further issue to consider, if we are to use the total IR luminosities as indicators of SFR, is the AGN contribution to this luminosity which could lead to an overprediction of the SFRs. This issue is especially important because our sources are selected to be AGN.

In a similar fashion to Symeonidis et al. (2010), we address this issue by normalizing a QSO template from Elvis et al. (1994) to the data point with the lowest luminosity from our photometric data set of 3.6–24 μm, as the AGN emission must be constrained by our photometry. If we use other AGN SED models [e.g. type 1 and type 2 AGN from Polletta et al. (2007)] we find that our estimates of the upper limits to the AGN luminosities and ratios of AGN to total IR luminosities change little, ≲10 per cent (and therefore even less for the final SFR). Such model SEDs are broadly similar to the Elvis et al. (1994) templates which in the IR are generally flat (in νLν) to star formation, assuming that the star-forming component lies mid-IR is completely dominated by the AGN, while conservative, also does not have a strong effect on the final SFR due to the low AGN fraction.

3.3 Comparison between radio and IR luminosities

We calculate the total IR luminosities of all SPIRE-detected sources in order to confirm our method of measuring these luminosities by comparison with the radio/far-IR correlation seen in local SFGs and now confirmed at higher redshifts (Seymour et al. 2009; Ivison et al. 2010). Additionally, by extrapolating this empirical correlation to higher luminosities we can assess the contribution of star formation to the radio luminosities of the sources detected by SPIRE in our two redshift samples. The IR luminosity has a large scatter which is largely due to the moderate-redshift sub-sample having lower IR AGN luminosities (∼10^{11} L_☉) than the high-redshift sub-sample (∼10^{12} L_☉), although we observe no trend with radio luminosity within a sub-sample.

We then estimate the AGN contribution to the total IR luminosity by integrating the QSO template in the 8–1000 μm region and subtract this from our total IR luminosity to obtain a star-forming IR luminosity for each object. We can then convert this star-forming IR luminosity to an SFR using the Kennicutt (1998) relation. In Fig. 4, we show the AGN IR luminosity and the ratio of AGN to total IR luminosity as a function of radio luminosity density for the radio sources detected by SPIRE in our two redshift samples. The ratio of AGN to total IR luminosity tends to be low, under 0.3 bar one source, consistent with the results seen in Hatziminaoglou et al. (2010), and averages around 0.15. As a check, we apply the simultaneous AGN/starburst template fitting routine used by Hatziminaoglou et al. (2010) to the radio-loud AGN studied here and we find similar total IR luminosities and AGN fractions. Therefore, the final SFRs we derive are not very sensitive to our choice of model starburst and AGN SEDs. Our assumption that the mid-IR is completely dominated by the AGN, while conservative, also does not have a strong effect on the final SFR due to the low AGN fraction.

3.4 Stacking the non-detections at 250 μm

We can obtain an approximate constraint on the far-IR luminosity of the radio-loud AGN not detected at 250 μm in each sample
by employing stacking techniques to obtain mean 250-μm flux densities for these sources. By assuming the same distribution of redshifts, IR SED types and ratios of AGN to total IR luminosity, we can argue that the mean SFRs of the undetected and detected redshift ranges. Therefore, we stacked the 11 and seven sources not detected at 250 μm in each sub-sample and found the mean flux densities reported in Table 2. The uncertainties in flux densities of the stacked sources are simply those of the mean.

### 3.5 SFRs in local (z < 0.1) radio-loud AGN

In order to examine any evolution of the mean SFR of radio-loud AGN over cosmic time, we need a local baseline to compare with. Recently published Spitzer/MIPS observations of the local (z < 0.1) 3CRR sample (Dicken et al. 2010) provide an excellent opportunity to assess star formation in the nearby radio-loud population. The 1.4-GHz luminosity densities of this sample, derived from the 5-GHz values in Dicken et al. (2010) assuming α = −0.75 and Sν ∝ να, fall within the 25 < log(L_{1.4}/W Hz⁻¹) < 26.5 range of our sub-sample selection. The 3CRR sources were selected to only include sources with Fanaroff–Riley Class II (FRII) morphologies (i.e. those with radio lobes which are brightest at their edges; Fanaroff & Riley 1974). However, the lower radio luminosity density limit used in our work very closely corresponds to the luminosity density, log(L_{1.4}/W Hz⁻¹) = 25.1, at which the radio-loud population switches from mostly containing Class I sources to mostly containing Class II sources. Furthermore, this local sample is not sensitive to the low end of our radio luminosity density range at z = 1 and therefore may not be 100 per cent complete. Dicken et al. (2010) derived rest-frame 70-μm luminosities from their Spitzer/MIPS observations which they compare with the [O III] emission-line luminosities of the local 3CRR sample. They found a broad correlation implying that generally the 70-μm luminosity is due to the AGN. However some 3CRR sources, which show evidence of star formation from their optical spectra, generally lie above this correlation, i.e. they have an excess of 70-μm luminosity compared to the [O III] emission. These authors postulate that this 70-μm excess could be due to star formation.

Here, we estimate the range of mean SFR in this sample using two assumptions. To obtain an upper limit, we assume that all of the 70-μm luminosity is due to star formation. To obtain a lower limit, we use the linear regression fit by Dicken et al. (2010) to the correlation of the O III and 70-μm luminosities to estimate the AGN-only 70-μm luminosity. We then subtract the AGN luminosity from the total 70-μm luminosity for all sources lying more than 0.3 dex above the correlation in order to obtain a starburst-only 70-μm luminosity. In both cases, we convert the 70-μm luminosities to total IR luminosities using the relation of Symeonidis et al. (2008) and then to SFRs using the Kennicutt (1998) relation as before. Due to the size of the sample and the influence of one very luminous source, we use the median-inferred SFR and find that the range of typical SFRs for the local 3CRR sample is 3.4–4.2 M⊙ yr⁻¹ from these two assumptions.

### 4 RESULTS

In Table 2 we report the mean SFR, (SFR), of the radio-loud AGN detected at 250 μm in each sub-sample. The SFRs of individual sources are derived from the total IR luminosities, minus the AGN contribution (see Section 3.2), using the conversion factors of Kennicutt (1998). We find values of 92 ± 28 and 914 ± 274 M⊙ yr⁻¹ in the moderate- and high-redshift bins, respectively. For the sources undetected at 250 μm, we find stacked 250-μm flux densities which are a factor of 11 and 7 lower than the mean flux densities of the detected sources (see Table 2) for the moderate- and high-redshift sub-samples, respectively. It is unsurprising that undetected sources have a mean flux density lower than those detected, but the fact that they are considerably lower (i.e. not just below our 3σ cut) suggests that these radio-loud AGN have a wide range of intrinsic SFRs. We report the SFRs of the undetected sources in Table 2 obtained from the ratio of the mean 250-μm flux densities of the detected and undetected sources and the measured SFR of the detected sources. Then we estimate the total mean SFR in each subset by combining the mean SFR of the detected and undetected sources weighted by the number in each group. The estimated total mean SFRs for the total sample are therefore 29.5 ± 11.6 and 581 ± 143 M⊙ yr⁻¹ for the moderate- and high-redshift bins, respectively.

The moderate-redshift sample is complete within the uncertainties of the S-cubed simulation (we find 15/16 predicted sources in this redshift/luminosity density parameter space). Hence, we can directly calculate the mean SFR of the low-redshift sample by summing the observed SFRs and dividing by the number sources. The uncertainties are simply those of the measured SFRs, which directly come from the uncertainties in the IR luminosities, combined with the 30 per cent uncertainty in the S-cubed model. As the latter are so much greater than the former, our uncertainties are dominated by the conservative uncertainties we used in S-cubed. We find a
mean SFR for this sub-sample of $29.5 \pm 11.6 \, M_{\odot} \, \text{yr}^{-1}$ which is equivalent to the range of values of $18-41 \, M_{\odot} \, \text{yr}^{-1}$.

As we saw from Fig. 2 the high-redshift sub-sample is incomplete, although we can quantify the incompleteness from comparisons to the S-cubed simulation. The number of radio-loud AGN expected from S-cubed is given in Table 2. We cannot estimate the properties of sources not included in our high-redshift sample due to lack of redshift information. However, we can estimate likely lower and upper limits on the mean SFR from two simple assumptions. First, to estimate the lower limit we assume that all the sources missed have SFRs of zero and then scale the mean SFR by the incompleteness (i.e. the lower limit is $\frac{10}{16} \times \text{the mean SFR for the observed fraction}$). While 24 per cent of the sources with unknown redshifts have 250-μm detections, we have no way of knowing how many of these fall into our high-redshift sub-sample; hence, this method of determining our lower limit is the most robust approach. Secondly, for the upper limit we assume that all sources not included have mean SFRs identical to the detected fraction, i.e. the upper limit is simply the measured mean SFR for the detected fraction. Hence, we calculate the range of mean SFRs for the high-redshift sub-sample to be $80-581 \, M_{\odot} \, \text{yr}^{-1}$.

We compare these constraints with those found for the local 3CRR sample and the recent results of Hardcastle et al. (2010) in Fig. 6 who measured IR luminosities from Herschel-ATLAS observations of radio sources occupying a similar region of redshift/luminosity parameter space. We see an increase in the mean SFR of radio-loud AGN with cosmic look-back time. In the local Universe we found the mean SFR of $\sim 3.4-4.2 \, M_{\odot} \, \text{yr}^{-1}$, whereas at moderate redshifts, $0.4 < z < 0.9$, we constrain it to be approximately five to 10 times greater and in our high-redshift sample we find it to be $\sim 20-150$ times greater. While these ranges of mean SFRs are wide, we observe a clear trend of increasing mean SFR with redshift in radio-loud AGN in the luminosity density range $25 < \log(L_{1.4}/\text{W Hz}^{-1}) < 26.5$, a trend that is also seen over a smaller redshift range in the results of Hardcastle et al. (2010).

We can quantify this rate of increase by fitting a straight line through the shaded regions of Fig. 6 via linear regression. We then find that the mean SFR of radio-loud AGN in this luminosity range evolves as $(1+z)^{\alpha}$, where we measure the value of $Q = 4.2 \pm 0.8$. This value for the evolution is strong and greater than that measured for the evolution of the star-forming luminosity function (which typically has values of $Q \sim 3$ as traced by IR surveys; Le Floch et al. 2005; Huynh et al. 2007; Magnelli et al. 2009; Rodighiero et al. 2010). We can also compare our results with the mean SFRs of high-redshift AGN selected at other wavelengths. The mean SFRs of X-ray-selected AGN, $L_{2-10 \, \text{keV}} > 10^{43} \, \text{erg s}^{-1}$, have been recently studied by Shao et al. (2010) and Lutz et al. (2010) who found that such sources have mean SFRs within, but at the low end of, the range of values found in our high-redshift bin. We illustrate these results in Fig. 6 using the same Kennicutt total IR luminosity to SFR conversion as before and converting the Shao et al. 60-μm monochromatic luminosities using the formula presented in Symeonidis et al. (2008). Also, Hatziminaoglou et al. (2010) found a similar range of SFRs for a heterogeneous sample of AGN above $z = 1$, suggesting that this increase is common to different types of AGN activity.

If we sum the observed star formation in each redshift bin, we can calculate the comoving SFR density due to the host galaxies of the radio-loud AGN in each redshift sub-sample. We find values of $\sim 2.5 \times 10^{-5} \, M_{\odot} \, \text{yr}^{-1} \, \text{Mpc}^{-3}$ for the moderate-redshift bin and $1-5 \times 10^{-4} \, M_{\odot} \, \text{yr}^{-1} \, \text{Mpc}^{-3}$ for the high-redshift bin. For the local redshift bin, the star formation density due to the host galaxies of the radio-loud AGN is $\sim 4 \times 10^{-5} \, M_{\odot} \, \text{yr}^{-1} \, \text{Mpc}^{-3}$. We can compare these SFR densities with the globally measured SFR history from a variety of different methods (e.g. Hopkins & Beacom 2006). We observe that the relative contribution of the host galaxies of radio-loud AGN to the total comoving SFR density increases with redshift from $\sim 0.0004$ per cent in the local sample to $\sim 0.03$ and $\sim 0.1-0.5$ per cent for the moderate- and high-redshift samples, respectively.

In Fig. 7, we show the $\langle \text{SFR} \rangle$ as a function of radio luminosity density for each of our two redshift sub-samples. We calculate upper and lower limits for each luminosity density bin as we did for the whole sample. The upper and lower limits are indicated by the grey-shaded regions. Note that due to the fact that we only detect 4/15 sources in the moderate-redshift sample, we have to increase the bin size by a factor of 3 compared to the high-redshift sample. We also overlay the upper and lower limits for the whole of each sub-sample as indicated by the dashed lines. We see no evidence for any trend of mean SFR with radio luminosity for either sub-sample, although the constraints for the highest radio luminosity density bin of the high-redshift sample are not so strong.

5 DISCUSSION

We observe that radio-loud AGN in the distant Universe have an increasing mean SFR with cosmological look-back time in the $25 < \log(L_{1.4}/\text{W Hz}^{-1}) < 26.5$ radio luminosity density range. In the local Universe, $z < 0.1$, the mean SFR of the 3CRR sample is five to 10 times less than that in a moderate-redshift sample, $0.4 < z < 0.9$. We note that the 3CRR sample was also selected on FRII radio morphology which suggests that we may not be comparing identical populations, and it may not be 100 per cent complete. Another recent study has examined the IR luminosities of bright radio sources with Herschel-ATLAS observations of the GAMA-9h field.
The contribution to the SFR density of the host galaxies of radio-loud AGN in the high-redshift bin is interesting as the SFR density at this epoch is dominated by LIRGs and ULIRGs (Le Floc'h et al. 2005; Seymour et al. 2010). As 0.1–0.5 per cent of the SFR density consists of LIRGs and ULIRGs which host the radio-loud AGN, we can infer a duty cycle of 0.001–0.005 for radio-loud AGN activity in such sources, assuming that each LIRG and ULIRG goes through at least one radio-loud phase. The typical time-scale of a radio-loud phase of an AGN is around ~10 Myr for extended radio sources (Miley 1980) and likely shorter for the less luminous sources with smaller radio lobes considered here. Given this lifetime and the estimated duty cycle of 0.001–0.005, we can estimate that LIRGs and ULIRGs undergo a radio-loud AGN phase every 2–10 Gyr. Hence, during the 3-Gyr time-span covered by the high-redshift sub-sample, we could expect perhaps one major phase of radio-loud AGN activity at a rate similar to that expected from major mergers (Hopkins et al. 2010).

The feedback models which quench star formation by evoking a radio-loud phase (e.g. Bower et al. 2006; Croton et al. 2006) are most important at late times, i.e. below z < 1, but they must occur at higher redshifts in order to prevent the most massive galaxies, formed at early times, from growing significantly more. However, in this work we observe many AGN in our high-redshift sub-sample which are in a state equivalent to the ‘radio-mode’ feedback of Croton et al. (2006) and Bower et al. (2006) and simultaneously have very high SFRs while feedback processes are predicted to be occurring.

With a similar radio luminosity cut to our moderate-redshift sub-sample, Hardcastle et al. (2010) found a mean SFR of between 20 and 50 M⊙ yr⁻¹, increasing across our moderate-redshift bin (see Fig. 6). This range of mean SFRs is consistent with that found here, 18–41 M⊙ yr⁻¹, allowing for the slightly different source selection, the different method of estimating IR luminosities and the fact that these authors do not subtract any AGN contribution from the total IR luminosity.

We find the increase in the mean SFR of radio-loud AGN hosts [parametrized as (1 + z)^Q, Q = 4.2 ± 0.8] to be greater than that of the IR luminosity function which traces the evolution of the general star-forming population. This greater rate of increase with redshift, compared to the regular star-forming population, suggests that some of the star formation may be directly associated with the radio-loud AGN activity. The increase in mean SFR with redshift of AGN is also seen in X-ray-selected AGN (e.g. Lutz et al. 2010; Shao et al. 2010) and in a heterogeneous sample of AGN (Hatziminaoglou et al. 2010). Alternatively, our results could reflect an increase in the stellar mass of the host galaxy, since high stellar mass galaxies have SFRs which increase with redshift (e.g. Juneau et al. 2005). This interpretation would fit in with the recent Tadhunter et al. (2011) result who found that at low redshifts, z < 0.7, not all ULIRGs are massive enough to host radio-loud AGN. If the stellar masses of ULIRGs increase with redshift, then ULIRGs would be more likely to host radio-loud AGN at higher redshifts.

While it is likely that the redshift information for the high-redshift sample is biased towards sources that have bright 24-μm flux densities (see Section 2.1), our approach of determining a range of mean SFRs given two extreme assumptions alleviates much of the concern about selection bias. The remaining principle source of uncertainty is the S-cubed model, used to quantify how complete our sub-samples were. As discussed earlier, our uncertainties in S-cubed are very conservative. S-cubed treats the AGN and SFGs as separate populations, i.e. it does not include hybrid radio sources exhibiting both processes simultaneously. We can thereby compare the expected number of radio-loud AGN regardless of whether there is ongoing star formation in their hosts or not. The contribution to the SFR density of the host galaxies of radio-loud AGN in the high-redshift bin is interesting as the SFR density at this epoch is dominated by LIRGs and ULIRGs (Le Floc'h et al. 2005; Seymour et al. 2010). As 0.1–0.5 per cent of the SFR density consists of LIRGs and ULIRGs which host the radio-loud AGN, we can infer a duty cycle of 0.001–0.005 for radio-loud AGN activity in such sources, assuming that each LIRG and ULIRG goes through at least one radio-loud phase. The typical time-scale of a radio-loud phase of an AGN is around ~10 Myr for extended radio sources (Miley 1980) and likely shorter for the less luminous sources with smaller radio lobes considered here. Given this lifetime and the estimated duty cycle of 0.001–0.005, we can estimate that LIRGs and ULIRGs undergo a radio-loud AGN phase every 2–10 Gyr. Hence, during the 3-Gyr time-span covered by the high-redshift sub-sample, we could expect perhaps one major phase of radio-loud AGN activity at a rate similar to that expected from major mergers (Hopkins et al. 2010).

The feedback models which quench star formation by evoking a radio-loud phase (e.g. Bower et al. 2006; Croton et al. 2006) are most important at late times, i.e. below z < 1, but they must occur at higher redshifts in order to prevent the most massive galaxies, formed at early times, from growing significantly more. However, in this work we observe many AGN in our high-redshift sub-sample which are in a state equivalent to the ‘radio-mode’ feedback of Croton et al. (2006) and Bower et al. (2006) and simultaneously have very high SFRs while feedback processes are predicted to be occurring.

6 CONCLUSIONS

We have examined the incidence of far-IR emission and inferred SFR of luminous radio-loud AGN in a moderate-redshift, 0.4 < z < 0.9, and a high-redshift sub-sample, 1.2 < z < 3, as well as in a local, z < 0.1, comparison sample. We have

(i) constrained the mean SFR of radio-loud AGN to be 3.4–4.2, 18–41 and 80–581 M⊙ yr⁻¹ for the local, moderate- and high-redshift samples, respectively; hence, we measure the evolution of the mean SFR to be ~(1 + z)^4.2±0.8;

(ii) observed no strong trends of SFR with radio luminosity in any redshift bin;

(iii) estimated that the host galaxies of radio-loud AGN in the high-redshift sub-sample contribute 0.1–0.5 per cent to the total SFR density at that epoch and if all LIRGs and ULIRGs have a radio-loud phase, we infer a duty cycle of 0.001–0.005 in such sources.

These results demonstrate that in the distant Universe a considerable amount of star formation is occurring in galaxies hosting a radio-loud AGN, consistent with the frequent evidence for high SFRs in classic high-redshift radio galaxies. The mean SFR evolves more quickly than the IR luminosity function implying that some of the star formation is directly related to the radio-loud AGN activity. Both starburst and active nuclear processes have relatively short time-scales, so their co-existence in many objects suggests that bursts of star formation and jet activity are either quite common or connected via ‘feedback’. But is the jet initiating or quenching star formation, or are the processes independent? We cannot answer
such questions here, but we shall be able to do so with follow-up of individual sources (to search for outflows of jet-triggered star formation or for mergers triggering both) and with the huge sample that will be provided by the full HerMES data set combined with improved redshift information.

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