The sub-mJy radio sky in the Extended Chandra Deep Field-South: source population

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ABSTRACT
The sub-mJy radio population is a mixture of active systems, that is star-forming galaxies (SFGs) and active galactic nuclei (AGNs). We study a sample of 883 radio sources detected at 1.4 GHz in a deep Very Large Array survey of the Extended Chandra Deep Field-South that reaches a best rms sensitivity of 6 µJy. We have used a simple scheme to disentangle SFGs, radio-quiet (RQ), and radio-loud (RL) AGNs based on the combination of radio data with Chandra X-ray data and mid-infrared observations from Spitzer. We find that at flux densities between about 30 and 100 µJy, the radio population is dominated by SFGs (~60 per cent) and that RQ AGNs become increasingly important over RL ones below 100 µJy. We also compare the host galaxy properties of the three classes in terms of morphology, optical colours and stellar masses. Our results show that both SFG and RQ AGN host galaxies have blue colours and late-type morphology while RL AGNs tend to be hosted by massive red galaxies with early-type morphology. This supports the hypothesis that radio emission in SFGs and RQ AGNs mainly comes from the same physical process: star formation in the host galaxy.

Key words: catalogues – galaxies: active – galaxies: star formation.

1 INTRODUCTION
The two main processes that contribute to the extragalactic continuum radio emission at 1.4 GHz are the non-thermal emission associated with relativistic electrons powered by active galactic nuclei (AGNs) and the synchrotron emission from relativistic electrons in supernova remnants. The latter is therefore a tracer of star formation activity in galaxies. While the bright radio sky is dominated by the emission driven by ‘radio-loud’ (RL) AGNs, at fainter flux densities (<1 mJy) the contribution from star-forming galaxies (SFGs) becomes increasingly important (e.g. Prandoni et al. 2001; Seymour et al. 2008; Smolčić et al. 2008; Padovani et al. 2009). Moreover, recent work has revealed the presence of a third population of sources in the sub-mJy radio sky, the ‘radio-quiet’ (RQ) AGNs (e.g. Padovani et al. 2009). These sources show the presence of AGN activity in one or more bands of the electromagnetic spectrum [e.g. optical, mid-infrared (MIR), X-ray] but the origin of their radio emission has been a matter of debate. It has been proposed that they represent scaled versions of RL AGNs with mini radio jets (e.g. Giroletti & Panessa 2009) or that their radio emission comes from star formation in the host galaxy (e.g. Kimball et al. 2011; Padovani et al. 2011). Disentangling the two emission mechanisms is important to investigate the circumstances under which they originate, for example the host galaxy properties, and possibly to study the connection between AGN and star formation activity. Most of the radio sources in surveys as deep as the one discussed in this paper are barely resolved or unresolved. So radio observations alone generally cannot be used to distinguish between AGN and star formation-driven sources; hence, the need for a multiwave-length approach. For example, Padovani et al. (2009) showed that the ‘standard’ definitions of radio loudness, which are based on radio-to-optical flux density ratios, R, and radio powers, are clearly insufficient to identify RQ AGNs in faint radio samples. This is because these also include star-forming and radio galaxies; both of these classes are or can be, respectively, characterized by low R and low radio powers as well. Padovani et al. (2011) showed instead that a proper classification of faint radio sources requires a combination of radio, IR and X-ray data. Here, we propose a new simple classification scheme, which is an upgrade of that used by Padovani et al. (2011). The paper is organized as follows. We present our sample and the data used for the classification of the radio sources.
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in Section 2. Our classification scheme is presented in Section 3. In Section 4, we describe the relative contribution of the different source types to the radio population. The host galaxy properties are analysed in Section 5. In Sections 6 and 7, we discuss and summarize our results. Our definitions of AGN, RQ and RL sources follow those of Padovani et al. (2011). In this paper, we use magnitudes in the AB system, if not otherwise stated, and we assume a cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \).

2 SAMPLE AND DATA

2.1 Radio catalogue, optical–IR counterparts and redshifts

We consider a sample of 883 radio sources detected at 1.4 GHz in a deep Very Large Array (VLA) survey of the Extended Chandra Deep Field-South (E-CDFS) that reaches a best rms sensitivity of 6 \( \mu \text{Jy} \). The average \( 5\sigma \) flux density limit is 37 \( \mu \text{Jy} \) and the spatial resolution is 2.8 arcsec \( \times 1.6 \text{arcsec} \). A description of the survey strategy and the data reduction details are given in Miller et al. (2013). Using the wealth of optical and infrared (IR) data available in the E-CDFS, we were able to identify the optical/IR counterpart for 839 (94 per cent) radio sources using a likelihood ratio technique (Bonzini et al. 2012). Combining data from the literature and newly acquired spectra, we assigned a reliable spectroscopic redshift to 274 sources. Including photometric redshift the number of sources with measured redshift increases to 678 and their average redshift is \( z \sim 1.1 \). The accuracy of the photometric redshift is around 6 per cent (Bonzini et al. 2012). The majority of the objects without a redshift are not detected at optical wavelengths. Their counterparts can be detected only at longer wavelengths, in the near-infrared (NIR) or MIR. Therefore, spectroscopic observations are challenging and photometric estimates, based on a few photometric points, are not robust. In other cases, the lack of photometric redshift information is due to a less rich multiwavelength coverage, especially in the outskirts of the field.

2.2 MIR data

MIR wavelengths can be used to unveil the presence of an AGN (see Section 3.1.3). Therefore, we used deep Spitzer InfraRed Array Camera (IRAC) and Multiband Imaging Photometer for Spitzer (MIPS) data. The IRAC data were obtained as part of the Spitzer IRAC/MUSYC Public Legacy Survey in the Extended CDF-South (SIMPLE) survey (Damen et al. 2011). It covers an area of about 1600 arcmin\(^2\) centred on the E-CDFS. The typical \( 5\sigma \) flux density limits are 1.1, 1.3, 6.3 and 7.6 \( \mu \text{Jy} \) at 3.6, 4.5, 5.8 and 8.0 \( \mu \text{m} \), respectively. We also use MIPS 24 \( \mu \text{m} \) data from the Far-Infrared Deep Extragalactic Legacy (FIDEL) survey (Dickinson & FIDEL Team 2007). This survey covers, at 24 \( \mu \text{m} \), \( \sim 90 \) per cent of the VLA area considered in this paper and the typical flux density limit (\( 5\sigma \)) is 30 \( \mu \text{Jy} \). To associate the correct MIR photometry with our radio sources, we cross-correlated the position of their optical/IR counterparts with the SIMPLE and FIDEL catalogues, after correcting for the median offset in right ascension and declination between the two samples. The matching radii are 0.7 arcsec for the SIMPLE catalogue and 1.5 arcsec for the FIDEL catalogue. A total of 91 and 88 per cent of the identified radio sources (839) have a match in the SIMPLE and FIDEL catalogues, respectively. For sources without 24 \( \mu \text{m} \) detection, we compute an upper limit to the 24 \( \mu \text{m} \) flux density. Since the exposure time varies across the field, the upper limit is extrapolated from the exposure map as \( \text{Flux}_{\text{lim}}(\sigma) = -1.4 + 1369.1/(t_{\text{exp}}) \), where \( t_{\text{exp}} \) is the exposure time in seconds and the flux density is in \( \mu \text{Jy} \).

Figure 1. X-ray luminosity as a function of redshift for RL AGNs (red squares), RQ AGNs (blue circles) and SFGs (green crosses) (see Section 3.2). The filled symbols represent X-ray detections, while the open symbols denote 3\( \sigma \) upper limits. X-ray detected sources with luminosity above the horizontal line are considered to be AGNs.

2.3 X-ray data

The E-CDFS has been mapped in the X-ray band by Chandra. A total of 129 radio sources have a counterpart in the 4 Ms observations of the CDFS presented in Xue et al. (2011) and another 99 in the main E-CDFS catalogue by Lehmer et al. (2005) obtained with shallower (250 ks) observations in each of four pointings. The list of the X-ray counterparts of the radio sources is given in Bonzini et al. (2012). We compute the X-ray luminosity (2–10 keV) to indicate the presence of AGN activity (see Section 3.1.2). Objects without X-ray counterpart, but with redshift (435 sources), have only an upper limit (3\( \sigma \)) on the X-ray luminosity obtained from aperture photometry on the X-ray images at the position of the radio source (Vattakunnel et al. 2012). A total of 44 radio sources lie in the outermost part of the field and have no X-ray observations available. The X-ray luminosity for our sample as a function of redshift is plotted in Fig. 1.

3 AGN OR SFG?

As discussed in Section 1, a proper classification of the faint radio sources requires a wealth of multiwavelength data. We have identified three diagnostics that can be used to split the population in the different classes of sources. In this section, we first describe these diagnostics and how they are used to classify the sources (Section 3.1) and our classification scheme (Section 3.2). Then, we present a series of checks that we performed to validate the method or to refine the classification of some peculiar sources (Sections 3.3–3.5).

3.1 Classification criteria

3.1.1 \( q \) values

It is well known that the far-IR and radio emission are tightly and linearly correlated in star-forming systems (e.g. Sargent et al.
values as a function of redshift is plotted in Fig. 2. For a parameter, which is the logarithm of the ratio of

\[ q = \log_{10}(S_{24 \mu m}/S_r) \]

as obtained in Sargent et al. (2010, and references therein). This is usually expressed through the so-called \( q \) parameter, which is the logarithm of the ratio of far-IR to radio flux density, as defined by Helou, Soifer & Rowan-Robinson (1985). Ideally, one would like to derive a bolometric \( q \), but typically insufficient data are available at longer wavelengths to do this reliably. For example, Padovani et al. (2011) were able to derive only upper limits on \( q \) for 50 per cent of the sources. In this paper, we therefore prefer to use \( q_{24obs} \), which is defined as

\[ q_{24obs} = \log_{10}(S_{24 \mu m}/S_r) \]

where \( S_{24 \mu m} \) is the observed 24 \( \mu m \) flux density and \( S_r \) is the observed 1.4 GHz flux density. The use of the observed flux densities rather than the rest-frame ones minimizes the uncertainties due to the modelling. In the case of resolved sources, we use integrated radio flux density (see Miller et al. 2013 for details). The distribution of the \( q_{24obs} \) values as a function of redshift is plotted in Fig. 2. For a given intrinsic spectral energy distribution (SED), this ratio has a redshift dependence. We assume that the IR and radio properties of high-redshift SFGs are similar to the local ones (e.g. Sargent et al. 2010). Therefore, to define a locus of SFGs, we compute \( q_{24obs} \) as a function of \( z \) using the SED of M821 as representative of the SFG class from \( z = 0 \) to the maximum redshift of our sources. For the radio spectra, we assume a spectral index \( \alpha_r = 0.7 \), as expected for a typical SFG (e.g. Ibar et al. 2010). The M82 template is normalized to the local average value of \( q_{24obs} \) as obtained in Sargent et al. (2010) (\( q_{24obs} = 1.31 \pm 0.10 \)) for sources with \( 0.08 < z < 0.23 \). The average spread for local sources is 0.35 dex (Sargent et al. 2010). We define the SFG locus as the region of \( \pm 2\sigma \) centred on the M82 template (see Fig. 2). Sources below this locus display a radio excess and therefore do not follow the far-IR–radio correlation and are classified as RL AGNs. Sources without 24 \( \mu m \) detection have only upper limits on the \( q_{24obs} \) value. These sources are classified as RL AGNs if their upper limit is smaller than the M82 template at the source redshift \( -\sigma \) (rather than \( -2\sigma \)).

For a small fraction (16 per cent) of the radio sources, 70 \( \mu m \) Spitzer photometry from the FIDEL survey is also available (Dickinson & FIDEL Team 2007). We can therefore check if we obtain the same classification using the longer wavelength data rather than the 24 \( \mu m \) flux density. Following the same procedure described above, we compute the \( q_{70obs} \) value for this subsample and define the corresponding SFG locus. We find excellent agreement (96 per cent of the cases) which validates our use of the 24 \( \mu m \) data for most of the sources.

### 3.1.2 X-ray luminosity

Sources with hard band X-ray luminosity above \( 10^{42} \) erg s\(^{-1} \) are considered to be AGN driven (e.g. Szokoly et al. 2004). A total of 162 sources in our sample have X-ray detection above this threshold. When only upper limits are available in the X-ray, we assume that the source is an SFG if there is no indication of black hole (BH)-driven activity in other bands (e.g. IRAC colours or \( q_{24obs} \)). In the central part of the field, where the 4 Ms Chandra observations are available, the upper limits on the X-ray luminosity are so faint that we miss only the most absorbed AGN. In the outer part of the E-CDFs, we only have the 250 ks Chandra observations and therefore it is possible that we are not sensitive even to moderate-luminosity \( (10^{42} < L_{2-10keV} < 10^{44} \) erg s\(^{-1} \)) AGNs. To avoid misclassifying sources as SFGs, sources with upper limits on their flux density \( 2 \sigma \) above the local background level and with upper limits on their X-ray luminosity minus 1\( \sigma \) larger than \( 10^{22} \) erg s\(^{-1} \) are classified as AGNs. A total of 23 sources satisfy this requirement.

### 3.1.3 IRAC colour space

Finally, we use the IRAC colour–colour diagram to help select AGNs. The AGN emission can heat up the surrounding dust that re-emits this energy in the MIR. If the AGN is sufficiently luminous compared to its host galaxy, the emission from the heated dust can produce a power-law thermal continuum across the four IRAC bands. Sources with this spectral shape occupy a specific region in the IRAC colour–colour diagram, the so-called Lacy wedge (Lacy et al. 2004). However, the ‘Lacy wedge’ is heavily contaminated by high-redshift SFGs (Donley et al. 2012). Therefore, to select AGNs we adopt the stricter criteria described in Donley et al. (2012) that are designed to minimize the contamination from both low- and high-redshift SFGs. These criteria require the flux density to monotonically increase in the four IRAC bands and the colours to be such that the source lies in the wedge plotted in Fig. 3. The completeness of this AGN selection method is strongly dependent on the AGN luminosity, being high for \( L_{2-10keV} \geq 10^{44} \) erg s\(^{-1} \) but relatively low (\( \lesssim 20 \) per cent) at lower luminosities (Donley et al. 2012). Type 2 Seyfert galaxies are also easily missed by this method. They are also incompletely for luminous AGNs with heavy obscuration and particularly bright host galaxies (Donley et al. 2012). A total of 85 sources in our sample satisfy these criteria. Eight of them were already classified as RL AGNs due to their \( q_{24obs} \) value and about half of them (44) have also X-ray luminosity above \( 10^{42} \) erg s\(^{-1} \). But 39 sources are classified as AGNs only because of their IRAC colours.

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1. From the Spitzer Wide-area Infrared Extragalactic (SWIRE) Legacy survey library, Polletta et al. (2007).
2. We define the spectral index as \( S_v \propto v^{-\alpha} \).
2.0 arcsec. In the central part of the region with only 250 ks of Chandra observations. Even assuming the mean redshift of the sample (z = 1), their X-ray luminosity in the total band is greater than 10^{42} erg s^{-1} and therefore we classify them as AGNs. None of them are classified as RL AGNs based on their upper limit on the $q_{24obs}$ value. Most of them are in the ‘Donley’ wedge too, but four are ‘new’ RQ AGNs. For all the other 126 identified radio sources without measured redshift, we do not have enough evidence to reveal the presence of an AGN (only upper limits on the X-ray luminosity, not in the ‘Donley wedge’, and not below the SFG locus), and therefore we conservatively consider them as SFGs. Note that a fraction of these could be RQ AGNs.

3.4 Unidentified sources

There are 44 sources without any optical, IR or X-ray counterpart. For these, the only information we have is the radio flux density. All but four of them (RID 1, 78, 853 and 865) have been observed by the FIDEL survey, and hence we have an upper limit on their 24 µm flux density. Having no information about the source redshift we assume $z = 3$ (see discussion in Section 3.3) to find additional RL AGNs. Out of the 40 sources for which we can compute an upper limit on the $q_{24obs}$, we classify four more objects as RL AGNs.

Note that sources without redshift and unidentified sources are not included in the analysis of host galaxy properties presented in Section 5 since no reliable morphology, stellar mass and colours can be derived for these sources. Therefore, the possible overestimation of the number of SFGs discussed above should not affect our results.

3.5 Further checks

We have checked our classifications using additional data such as radio observations at other frequencies and optical and X-ray spectra. These checks are summarized below, from longer to shorter wavelength.

3.5.1 Inverted radio spectra sources

The E-CDFS has been also observed in the Australia Telescope Large Area Survey (ATLAS) 5.5 GHz survey (Huynh et al. 2012). This survey has an almost uniform sensitivity of $\sim 12$ µJy rms with a resolution of 4.9 arcsec $\times$ 2.0 arcsec. In the central part of the field, deeper VLA observations at 4.8 GHz are available, down to an rms noise of 7 µJy (Kellermann et al. 2008). We combine these data sets to compute the radio spectral index, $\alpha_r$, of our sources. We use the VLA measurements in the central part of the field and the ATLAS ones outside this region. A discrepancy between the flux density measured in the VLA and ATLAS surveys has been noted by Huynh et al. (2012). The ATLAS flux densities are about 20 per cent greater than the VLA ones and they have been therefore corrected before computing the spectral indices. We measured the radio spectral index for a total of 215 sources excluding the multiple component sources as the interpretation of their spectral index is complicated by their core-jet structure. An inverted radio spectrum ($\alpha_r < 0$) is the signature of compact core emission typical of radio AGNs (e.g. Kellermann & Pauliny-Toth 1969). Only one source (RID 640) with a reliable inverted radio spectrum has been initially classified as an SFG. It lies at the bottom of the SFG locus shown in Fig. 2, and has therefore been re-classified as an RL AGN.

3.5.2 VLBA sources

Middelberg et al. (2011) have detected 21 VLA-CDFS sources with the Very Long Baseline Array (VLBA) using a resolution of $\sim 0.025$ arcsec. With a flux density limit of $\sim 0.5$ mJy, very long baseline interferometry (VLBI) detections above $z > 0.1$ are most
likely to be due to AGN. Reassuringly, all of the 20 detected VLBA objects with $z > 0.15$ had been classified as RL AGNs by our method. The single object with $z < 0.15$ ($z = 0.08$) has a VLBI detection offset from the centre of the galaxy and quite a low core radio power ($\sim 5 \times 10^{21}$ W Hz$^{-1}$) and was therefore classified as an SFG by Middelberg et al. (2011), in agreement with our classification.

### 3.5.3 Optical spectra

The presence of broad lines or high-excitation emission lines in optical spectra is another indicator of AGN activity. Therefore, we inspected the spectra of the sources that we classify as SFGs, when available. Out of the 100 spectra that we inspected, none have broad emission lines and only one (RID 618) shows a high-excitation emission line (Ne $\lambda$). Therefore, we changed its classification to an RQ AGN. Many diagnostic methods based on line ratios, such as the Baldwin, Phillips & Terlevich (BPT) diagram (Baldwin, Phillips & Terlevich 1981), have been proposed in the literature (e.g. Kauffmann et al. 2003; Smolčić et al. 2006; Best & Heckman 2012). The spectral coverage of the optical spectra makes these methods feasible only for local sources ($z \lesssim 0.3$). In our sample, only 4 per cent of the sources have the required redshift and a good quality spectrum available. Therefore, we do not have the data for a statistically significant comparison with the spectral line ratio diagnostic methods.

### 3.5.4 R values

The rest-frame radio-to-optical flux density ratio $R$ can also be used as an indicator of radio loudness (e.g. Kellermann et al. 1989). Following Padovani et al. (2009), we define $R$ as the logarithm of the ratio between the rest-frame flux density at 1.4 GHz and in the $V$ band, which means that the ‘classical’ dividing line between RL and RQ AGNs is at $R \sim 1.4$. The numerator is computed using the observed radio spectral index, where available, or assuming $\alpha_r = 0.7$ in the case of sources with no detection at 6 cm, while the $K$-correction for the $V$-band flux density is computed interpolating the observed optical photometry at the rest-frame $V$-band wavelength. The optical photometry for our sources is taken from Cardamone et al. (2010) and Taylor et al. (2009). We obtained an estimate of $R$ for a total of 574 sources. The others have no detection in the observed optical and NIR wavelength ($K$ band) or lack a redshift estimate. The $R$ values are plotted versus $q_{24\text{obs}}$ in Fig. 4. At $z < 1$, SFGs and RQ AGNs are both characterized by low values of $R$, with mean of 0.5 and 0.6, respectively. These values increase as the redshift increases. This behaviour is due to our flux density limit: at high redshift we can detect only galaxies with high star formation rate (SFR). Such sources are usually dusty and, for a given optical luminosity, have higher IR emission. Therefore, they can have $R$ values as high as 2 but, at the same time, follow the radio–far-IR correlation indicating that the radio emission is due to star formation rather than to the presence of an RL AGN. On the other hand, RL AGNs span a wide range of $R$ values at all redshift. Therefore, we do not apply a cut in $R$ to separate RQ and RL AGNs since these include radio quasars and radio galaxies.

### 3.5.5 PAH

The top-left region in the IRAC colour–colour plot in Fig. 3, $\log(S_{8.0}/S_{5.8}) > 0.3$ and $\log(S_{5.8}/S_{3.6}) < 0$, is populated by sources whose SED is dominated by the polycyclic aromatic hydrocarbon (PAH) features, typical of SFGs. In particular, only low-redshift SFGs have IRAC colours that fall in this region since higher redshift objects tend to move to the bottom part of the plot. Only two (RID 568 and 438) among the ~80 sources in this region are classified as RL AGNs according to their $q_{24\text{obs}}$ value. All the others are SFGs according to our classification scheme. For these two objects, it is possible that the 24 $\mu$m flux density is underestimated. Indeed, the FIDEL catalogue is obtained using aperture photometry, and for local extended sources some of the flux density might be lost. These two sources have been re-classified as SFGs (in Fig. 2 they are the only two green points below the SFG locus).

### 3.5.6 X-ray spectral analysis and variability

Tozzi et al. (2009) and Vattakunnel et al. (2012) performed a full X-ray spectral analysis for the X-ray detected radio sources in the E-CDFS. They considered as further diagnostics to discriminate between AGNs and SFGs the intrinsic absorption in the X-ray spectrum and the presence of the iron emission line. Indeed, the detection of a significant intrinsic absorption reveals that the X-ray flux is dominated by nuclear emission (e.g. Alexander et al. 2005; Brightman & Nandra 2011). We adopt as a threshold a column density of $10^{22}$ cm$^{-2}$. Out of the 87 sources above this threshold, only three (ID 143, 397 and 734) were initially considered to be SFGs. We changed their classification to RQ AGNs. Another strong indicator of nuclear activity is the presence of a K-shell Fe line at 6.4 keV in the source spectrum (e.g. Nandra & Pounds 1994). Four sources, which were initially classified as SFGs, have a clear detection of the Fe line and were therefore re-classified as RQ AGNs. Finally, the time X-ray variability is another signature of the presence of an AGN. A total of 23 sources in our sample have X-ray variability with high confidence level (>97 percent) (Paolillo et al. 2004, Paolillo et al., in preparation). They were all already classified as AGNs according to our criteria.

To summarize, only 11 sources needed to be re-classified, supporting the validity of our classification method described in Section 3.2. The majority of them (6/11) are RQ AGNs that were previously classified as SFGs: in such systems only the X-ray spectral analysis has revealed the clear presence of an AGN, while the other indicators were inconclusive.

### 3.6 Results

According to the criteria described in the previous sections, out of the 883 radio sources, we identify 173 (19 per cent) RL AGNs, 208 (24 per cent) RQ AGNs and 502 (57 per cent) SFGs.

In Table 1, we report the classification for each radio source together with the information used to identify it. The identification number (column 1) corresponds to that given in Miller et al. (2013) and Bonzini et al. (2012). The position of the optical–IR counterpart is given in columns 2 and 3 (Bonzini et al. 2012). The table also includes the source redshift (column 5), the logarithm of the radio luminosity in W Hz$^{-1}$ (column 6), the logarithm of the unabsorbed X-ray luminosity in erg s$^{-1}$ (for undetected sources a 3$\sigma$ upper limit is given) (column 7), $q_{24\text{obs}}$ (column 8), the IRAC colours (columns 9 and 10), the radio spectral index (assumed to be =0.7 when not available) (column 11) and the rest-frame absolute $B$ magnitude (column 12). We also define a quality flag (QF) which ranges from 3, for secure classification, to 1, for a tentative classification (column 13). Sources for which all the criteria agree (or are not in contradiction) have QF = 3 (45 per cent of the sources). We assign
Figure 4. $R$ versus $q_{24\text{obs}}$. In the left-hand panel, the different symbols correspond to the three classes of sources: RL AGNs (red squares), RQ AGNs (blue circles) and SFGs (green diamonds). In the right-hand panel, the colour scale indicates the redshift.

Table 1. Classification of radio sources. A full version of the table is available in the online material.

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RID | RA  | Dec. | Class | z  | $Pr$ | $L_X$ | $q_{24\text{obs}}$ | log ($S_{5.8}/S_{3.6}$) | log ($S_{8.0}/S_{4.5}$) | $\alpha_r$ | $B$ magnitude | QF |
|-----|-----|-----|-------|-----|------|-------|------------------|------------------|------------------|-------|----------------|-----|
| 601 | 03:32:48.18 | $-27:52:56.60$ | RL AGN | 0.67 | 22.79 | 42.68 | 0.62 | 0.53 | 0.53 | – | – | 22.77 | 3 |
| 602 | 03:32:48.30 | $-27:56:26.91$ | SFG | 0.35 | 22.53 | <41.44 | 0.69 | 0.61 | 1.18 | 0.8 | – | 22.08 | 2 |
| 603 | 03:32:48.57 | $-27:49:34.36$ | SFG | 1.12 | 23.69 | 41.86 | 0.07 | 0.63 | 0.62 | 0.4 | – | 22.00 | 2 |
| 604 | 03:32:49.19 | $-27:40:50.49$ | RL AGN | 1.22 | 25.63 | 43.61 | 0.42 | 2.53 | 2.76 | 0.8 | – | 23.79 | 3 |
| 605 | 03:32:49.22 | $-28:03:44.64$ | RQ AGN | 0.64 | 22.89 | 42.44 | 0.86 | 0.53 | 0.53 | – | – | 23.77 | 3 |
| 606 | 03:32:49.33 | $-27:58:45.19$ | SFG | 2.21 | 24.84 | <42.96 | 0.16 | 1.25 | 1.49 | 0.8 | – | 24.61 | 1 |
| 607 | 03:32:49.39 | $-27:36:36.22$ | SFG | 0.64 | 22.87 | <42.28 | 0.69 | 1.07 | 0.79 | 1.3 | – | 22.33 | 3 |
| 608 | 03:32:49.42 | $-27:42:35.14$ | RL AGN | 0.98 | 23.56 | <42.12 | 1.03 | 0.75 | 0.92 | – | – | 23.11 | 3 |
| 609 | 03:32:49.92 | $-27:34:45.69$ | RQ AGN | 0.25 | 22.59 | <41.20 | 0.95 | 0.79 | 0.79 | 1.3 | – | 21.16 | 3 |
| 610 | 03:32:49.95 | $-27:34:32.74$ | SFG | 0.25 | 22.86 | <41.11 | 0.81 | 0.75 | 0.79 | 1.3 | – | 22.05 | 3 |
| 611 | 03:32:50.84 | $-27:31:41.16$ | SFG | 0.10 | 21.34 | <40.57 | 1.08 | 0.72 | 0.72 | 1.8 | – | 18.91 | 3 |
| 612 | 03:32:50.86 | $-28:03:17.64$ | SFG | – | – | – | – | – | – | – | – | 1 |
| 613 | 03:32:51.59 | $-27:59:18.46$ | SFG | 0.91 | 23.15 | <42.42 | 1.16 | 0.79 | 0.98 | – | – | 22.85 | 3 |
| 614 | 03:32:51.65 | $-27:39:36.79$ | RL AGN | 0.78 | 23.56 | – | 0.20 | 1.07 | 0.70 | 1.8 | – | 20.70 | 3 |
| 615 | 03:32:51.73 | $-27:49:51.02$ | RQ AGN | 0.74 | 22.89 | <41.80 | 0.84 | 0.84 | 0.84 | – | – | 22.00 | 3 |
| 616 | 03:32:51.79 | $-27:59:56.18$ | SFG | 0.53 | 22.95 | <41.96 | 0.78 | 0.90 | 1.15 | – | – | 20.43 | 3 |
| 617 | 03:32:51.84 | $-27:44:36.78$ | RQ AGN | 0.52 | 22.85 | <41.40 | 1.08 | 1.01 | 2.02 | 0.1 | – | 22.29 | 2 |
| 618 | 03:32:51.83 | $-27:42:29.49$ | RQ AGN | 1.03 | 23.44 | 42.58 | 0.88 | 0.68 | 1.00 | – | – | 23.18 | 3 |
| 619 | 03:32:51.92 | $-27:44:25.12$ | RL AGN | 0.53 | 23.00 | 41.20 | <0.80 | 0.48 | 0.38 | – | – | 22.37 | 3 |

QF = 2 to sources with $q_{24\text{obs}}$ value just above the RL AGN threshold ($q_{24\text{obs}}, M82 − 2\sigma< q_{24\text{obs}}< q_{24\text{obs}}, M82 − 1\sigma$). Sources without redshift but with clear signature of AGN activity (e.g. in the Donley wedge or with very low values of $q_{24\text{obs}}$ value) have also QF = 2. A total of 18 per cent of the sources have QF = 2. The remaining sources have classification with QF = 1. Examples of this last category are sources without redshift and without clear signature of AGN activity or without an optical/IR counterpart. Also sources with upper limits on the X-ray luminosity $>10^{42}$ erg s$^{-1}$, not in the Donley wedge, and above the RL AGN threshold have QF = 1. These sources are classified as SFGs but, even if we can exclude that they are RL AGNs, there might be a contamination from RQ AGNs. Deeper X-ray observations are needed to discriminate between the two classes of sources.

In Fig. 5, we show the radio power distribution for the three classes of sources. The distribution of the RL AGNs is the widest since it includes both low-power radio galaxies and the most powerful radio AGNs. This means that with a simple cut in $P_r$, one would exclude a significant fraction of RL sources. We also note that only 44 RL AGNs out of a total of 177 have X-ray luminosity greater than $10^{42}$ erg s$^{-1}$ (35 sources) or are MIR-selected AGNs (9 sources). All the other are identified as AGNs only based on their radio emission through the $q_{24\text{obs}}$ parameter. We expect most of these X-ray undetected AGNs to be intrinsically X-ray faint low-power radio galaxies (e.g. Padovani 2011), but there could also be a fraction of heavily obscured sources (e.g. Del Moro et al. 2013). Radio observations are almost unaffected by dust extinction and therefore we can in principle detect even the most obscured systems. The
Radio source populations in the E-CDFS

mean radio power for SFGs is $\sim 10^{23}$ W Hz$^{-1}$ but there are also galaxies with $P_r$ as high as $10^{24.5}$ W Hz$^{-1}$. These sources have all redshift $> 2$ but $QF = 1$.

We stress that our classification scheme tends to overestimate the number of SFGs. We consider AGNs only those sources that have strong evidence of the presence of an AGN in one of the wavelength range considered: radio, MIR and X-ray.

With this new scheme, we confirm 80 per cent of the classification for the sample of 193 sources presented in Padovani et al. (2011). The remaining sources were re-classified because of new redshift measurements, different optical/IR counterparts, deeper X-ray data and deeper 24 $\mu$m data, which allowed us to compute their $q$ value, whereas previously only an upper limit was available.

4 THE SUB-MJY POPULATION

To investigate the relative contribution of the different source types to the radio population as a function of the flux density, we exclude the outermost part of the field, since there we do not have enough ancillary multiwavelength data to provide reasonable photometric redshift and therefore the classification of the sources is more uncertain. We then consider the subsample within an area of 0.282 deg$^2$ where we have photometric redshift coverage (see Bonzini et al. 2012 for details), which includes 779 radio objects for which we have redshift for 90 per cent of the sources with optical/IR counterpart

(compared to the 81 per cent of the whole radio sample). We consider radio sources down to an rms noise of 6.5 $\mu$Jy or a $5\sigma$ flux density limit of 32.5 $\mu$Jy. The sensitivity of our sample is somewhat a function of the position in the field, although a much less strong one than for the CDFS sample of Kellermann et al. (2008). Consequently, the area of the sky covered at any given flux density is flux density dependent (see Miller et al. 2013). To estimate the relative fractions of sources as a function of the flux density, we therefore weigh each source by the inverse of the fraction of the area corresponding to that value. The results are plotted in Fig. 6, which shows that AGNs dominate at large flux densities ($\gtrsim 1$ mJy) but SFGs become the dominant population below $\approx 0.1$ mJy. Similarly, RL AGNs are the predominant type of AGNs above 0.1 mJy but they drop fast at lower flux densities.

In more detail, AGNs make up 43 $\pm$ 4 per cent (where the errors are based on binomial statistics; Gehrels 1986) of sub-milliJansky sources and are seen to drop at lower flux densities, going from 100 per cent of the total at $\sim 10$ mJy down to 39 per cent at the survey limit. SFGs, on the other hand, which represent 57 $\pm$ 3 per cent of the sub-milliJansky sample, are missing at high flux densities but become the dominant population below $\approx 0.1$ mJy, reaching 61 per cent at the survey limit. RQ AGNs represent 26 $\pm$ 6 per cent (or 60 per cent of all AGNs) of sub-milliJansky sources but their fraction appears to increase at lower flux densities, where they make up 73 per cent of all AGNs and $\approx 30$ per cent of all sources at the survey limit, up from $\approx 6$ per cent at $\approx 1$ mJy. These results are in good agreement with those of Padovani et al. (2011).

5 HOST GALAXY PROPERTIES

5.1 Morphology

A fraction of our sample has Advanced Camera for Surveys (ACS)/Hubble Space Telescope (HST) images available. We use this subsample to characterize the morphology of the host galaxy of our sources. We obtain the morphological information from the publicly available ACS-ACS General Catalog (Griffith et al. 2012). The ACS images have been fitted with the GALAPAGOS method (Häußler et al. 2011) that analyses the images through the GALFIT code (Häußler et al. 2007). The GALFIT code models each source with a Sérsic profile (Sérsic 1963), a parameter that describes the

Figure 5. Radio power distribution for SFGs (top), RQ AGNs (middle) and RL AGNs (bottom).

Figure 6. Relative fraction of the various classes of radio sources: SFGs (green diamonds), all AGNs (black triangles), RQ AGNs (blue circles) and RL AGNs (red squares). The error bars correspond to $1\sigma$ Poisson errors (Gehrels 1986).
intensity profile of a galaxy, after a convolution with a point spread function. In particular, we consider the results of the fit performed on the z-band (F850LP) ACS images. At the average redshift of our sample ($z = 1.1$), this filter corresponds to the rest-frame $B$ band. We exclude from our analysis all the sources for which GALFIT gives an unreliable fit [FLAG = 1 in the Griffith et al. (2012) catalogue]. Moreover, sources with z-band magnitude $\geq 24$ suffer large uncertainties on the Sérsic index measurements and are therefore excluded. Finally, we remove also low surface brightness galaxies since they are known to produce unreliable results (Griffith et al. 2012).

The total number of objects with good fit results is 362. Of these, 75 are RL AGNs, 60 RQ AGNs and 227 SFGs. The average redshift of this subsample is 0.76. For these sources, we have an estimate of the Sérsic index, which is generally lower for late-type galaxies, where the disc dominates the intensity profile, and larger in elliptical galaxies.

The Sérsic index distribution for the three classes is shown in Fig. 7. The majority of RQ AGNs and SFGs have Sérsic indices $\leq 2$ implying that the host galaxies of both classes are preferentially late-type objects. The distribution for the RQ AGNs is broader than the one of SFGs, but it is important to note that the results of the GALFIT fit tend to overestimate the Sérsic index in the presence of a bright central point source (Gabor et al. 2009). Therefore, the brightest Quasi Stellar Objects (QSOs) among the RQ AGNs can produce a tail at high Sérsic indices in the RQ distribution. Sérsic indices of RL AGNs instead peak around 4, a value typical of galactic bulges and early-type galaxies. Performing a Kolmogorov–Smirnov test (KS test), we find a significant difference ($>99.9$ per cent) between the Sérsic index distribution of RL AGNs and the other two classes. This result suggests that the host galaxies of RL AGNs are morphologically different from the host galaxies of RQ AGNs and SFGs: RL AGNs are preferentially hosted by elliptical galaxies while RQ AGNs and SFGs are found in late-type galaxies.

5.2 Stellar masses

To estimate the stellar mass of the host galaxies, we used an SED fitting technique. We modelled the observed photometry with two components: a galactic and an AGN component as in Bongiorno et al. (2012). For the AGN component, we use the Richards et al. (2006) mean QSO SED. We applied a Small Magellanic Cloud-like dust-reddening law (Prevot et al. 1984) and we consider different amount of dust extinction, $E_{B-V}$, from 0 to model obscured, type I AGN to 9 for the most obscured, type II sources, in steps of 0.1. For the galactic component, we use the stellar population synthesis models of Bruzual & Charlot (2003). Assuming a universal initial mass function from Chabrier (2003), we generate SEDs assuming different star formation histories (SFH): 10 exponentially declining SFH (SFR $\propto e^{-t/\tau}$) with e-folding times ($\tau$) ranging from 0.1 to 30 Gyr, four models with constant SFR (1, 5, 10, 50 M$_\odot$ yr$^{-1}$) and five models with rising SFH ($\tau = -0.5, -1, -5, -10, -15$). For each SFH, we generate SEDs for different ages from 50 Myr to 9 Gyr. We exclude the models with age larger than the age of the Universe at the source redshift. For the galactic component, we assume a Calzetti’s reddening law (Calzetti et al. 2000). We consider colour excess $E_{B-V}$ in the range $0 \leq E_{B-V} \leq 0.5$ in steps of 0.1. We impose the prior that $E_{B-V} < 0.15$ if Age$/\tau > 4$ to exclude models with large dust extinction in the absence of a significant SFR (Fontana et al. 2004; Pozzetti et al. 2007). The observed flux is modelled as the sum of the AGN and galactic component such as

$$f_{\text{obs}} = af_{\text{AGN}} + bf_{\text{GAL}},$$

where $a$ and $b$ are the normalization constants for the two templates. The best-fitting template combination and normalization are found using a standard $\chi^2$ minimization. The photometry for our radio sources is taken from the BV$R$-selected Cardamone et al. (2010) catalogue. We matched their catalogue with the position of our counterparts using a searching radius of 0.2 arcsec and we found 569 matches. For the remaining sources, we use the photometry from the K-selected Taylor et al. (2009) catalogue. We found 78 additional matches. Finally, for those sources not detected in both the BV$R$- and K-selected catalogues, we use the photometry from the Damen et al. (2011) IRAC-selected SIMPLE catalogue. We found 145 more sources but only 24 of them have a redshift and can therefore be used in the fitting procedure.

We fitted all sources with known redshift and at least eight photometric points in the wavelength range from the $U$ band to the 24 $\mu$m for a total of 655 sources (23 per cent RL AGNs, 23 per cent RQ AGNs and 54 per cent SFGs). Two examples of the fitting results are shown in Fig. 8.

From the best-fitting galaxy model, we derived the stellar mass of our galaxies. We excluded 24 sources whose flux density in the rest-frame $K$ band is dominated by the AGN ($f_{\text{AGN}} > 2f_{\text{GAL}}$), since the stellar mass measurement in these cases is too uncertain. The stellar mass distributions for the three classes are plotted in Fig. 9.
Our radio-selected SFGs have typical stellar masses of $10^{10.5} \, M_\odot$. The RL AGNs have on average higher stellar masses ($10^{11} \, M_\odot$), and a KS test shows that the stellar mass distribution of RL AGNs is different from that of the SFGs at the >99.9 per cent level. RQ AGN host galaxies have stellar masses slightly higher than SFG hosts. However, a KS test shows that the mass distributions of SFGs and RQ AGNs are not significantly different. Moreover, it is important to note that most of our RQ AGNs (76 per cent) are identified as AGN as their total X-ray luminosity is above $10^{42} \, \text{erg s}^{-1}$. It has been suggested in recent works (e.g. Aird et al. 2012; Bongiorno et al. 2012) that a threshold in X-ray luminosity introduces a bias towards higher host galaxy stellar masses. The probability of a galaxy hosting an AGN of a given Eddington ratio is independent of stellar mass, and the number density of AGNs increases for decreasing Eddington ratio. Therefore, in a flux density-limited sample, one can detect AGNs of low Eddington ratios only in the most massive galaxies. Considering this bias, we cannot conclude that the host galaxies of RQ AGNs are intrinsically different from the SFG ones.

We also note that only 20 per cent of our RL AGNs have X-ray luminosity greater than $10^{42} \, \text{erg s}^{-1}$ and therefore their high stellar masses cannot be explained by this effect. We then confirm the tendency of RL AGNs to be hosted by the most massive objects (e.g. Dunlop et al. 2003; Best et al. 2005).

5.3 Rest-frame colours

From the best-fitting galaxy model, we derived the rest-frame $U - B$ colours. These colours are commonly used to distinguish between evolved stellar population galaxies, which populate the so-called red sequence, and the young stellar population system usually found in the ‘blue cloud’ (e.g. Bell et al. 2004). In the left-hand panel of Fig. 10, we plot the measured rest-frame $U - B$ colours as a function of the stellar mass. RL AGNs show preferentially red colours confirming previous results (e.g. Dunlop et al. 2003). RQ AGNs and SFGs have instead a wider range of colours occupying both the blue cloud and the red sequence, as well as the region in between, called the ‘green valley’. But the red colours in these type of systems should probably be interpreted as a signature of dust obscuration rather than as an indication of old stellar population. This can be tested by considering the de-reddened colours. The intrinsic colours are derived from the best-fitting galaxy model corrected for dust extinction. The latter are shown in the right-hand panel of Fig. 10 as a function of the stellar mass. Comparing the left- and right-hand panels, we see more clearly the impact of dust reddening: RL AGN hosts, intrinsically characterized by old stellar population, are nicely displayed along the red sequence, while SFGs and RQ AGNs have moved towards bluer colours. In particular, it is interesting to note how the two types of radio AGNs
have very different host galaxies properties, in agreement with what was found from considering their morphology (see Section 5.1).

5.3.1 Rest-frame optical colours as classification method

Smolčić et al. (2008) present a method to separate SFGs from AGNs, based on the rest-frame optical colours. This makes use of the rest-frame colour $P1$ that is a linear combination of the colours obtained from the modified Strömgren filters, as described in Smolčić et al. (2006). In particular, according to Smolčić et al. (2008), a source with $P1 < 0.15$ is classified as an SFG while it is an AGN otherwise. This method does not apply to QSOs defined as point-like sources in the optical image (Smolčić et al. 2008). Therefore, we concentrate on the subsample described in Section 5.1 for which the results of the GALFIT analysis (Griffith et al. 2012) are available and with known redshift. After removing the point-like sources, we are left with 336 objects. We computed the rest-frame $P1$ colour for these sources from the best fit of the SED as in Smolčić et al. (2008). We find that this method recovers about 70 per cent of our RL AGNs, but only 25 per cent of our RQ AGNs. As described in Section 3.2, our RQ AGNs show clear evidence of AGN activity in the X-ray or in the MIR. The reason why these sources can easily be misclassified by a method based on optical colours is that the host galaxy can dominate the total emission at these wavelengths. RQ and RL AGNs have, on average, different host galaxy properties (see Section 5); therefore, using the rest-frame optical colours it is possible to identify the RL AGNs hosted by red, old galaxies, while it is difficult to find RQ AGNs as they share the same parameter space as SFGs.

5.4 The 4000 Å break

The strength of the 4000 Å break ($D_{4000}$) is a proxy for the mean stellar age of a galaxy. In Best et al. (2005), it has been used to separate starburst galaxies from RL AGNs. We computed the $D_{4000}$ for our sources from the best-fitting galaxy template obtained as described in Section 5.2. Deriving this quantity from the photometry, the uncertainties are large ($\sim 0.1$) as discussed in e.g. Smolčić et al. (2008). In Fig. 11, $D_{4000}$ is plotted as a function of the 1.4 GHz luminosity normalized by stellar mass. The dashed line marks the separation between RL AGNs and starburst galaxies as defined in Best et al. (2005). The majority (85 per cent) of our RL AGNs lie above the separation line, in agreement with what is expected for classical RLs. The RL AGNs below this line are on average less powerful and the host masses are smaller. A total of 86 per cent of our SFGs are below the separation line. Given the large uncertainties on our $D_{4000}$ measurements due to the lack of spectroscopy, we can conclude that our classification method is in good agreement with the one proposed by Best et al. (2005). We confirm that the strength of the 4000 Å break can be successfully used to separate SFGs from RL AGNs, especially for sources with large stellar masses. Note that also in the $D_{4000}$ versus $L_{1.4 GHz}/M_*$, RQ AGNs share the same parameter space as SFGs. Indeed, 83 per cent of our RQ AGNs are below the starburst–AGN separation line, indicating the presence of a young stellar population in their hosts. One more time we stress the need of a multiwavelength approach to identify
this population of AGNs, whose emission can be over-shone by the host galaxy one or be heavily absorbed at optical wavelength.

6 DISCUSSION

6.1 Selection caveats

As already mentioned, the major source of uncertainty in our scheme comes from the possible misclassification of low-luminosity RQ AGNs as SFGs where we do not have deep X-ray observations. To get a rough estimate of the magnitude of this effect, we considered only the area covered by the 4 Ms Chandra observations (i.e. the 7 arcmin radius around the centre). In this region, we have a flux density limit for the hard X-ray band of $\sim 3.2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (Xue et al. 2011) and we find 43 RQ AGNs and 63 SFGs. Using the flux density limit of the 250 ks observations ($\sim 5.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$; Lehmer et al. 2005), we would not detect 12 RQ AGNs that therefore would have been classified as SFGs having only an upper limit on their X-ray luminosity. From this comparison, we can estimate that the contamination to the SFG population from RQ AGNs in the outer part of the field is $\sim 16^{+2}_{-1}$ per cent (12/63+12).

A second source of contamination in our selection scheme can come from RL AGNs being classified as RQ AGNs due to strong 24 µm emission related to AGN heated dust. Indeed a strong contribution to the 24 µm from the AGN can boost the $q_{24\text{obs}}$ value in the SFG/RQ AGN locus at a given radio flux density. At $z \sim 1$, the mean redshift of our sample, the 24 µm emission corresponds to a rest-frame 12 µm emission. To estimate the AGN contribution to the total flux density at this wavelength, we use the correlation found by Gandhi et al. (2009) between the hard band (2–10 keV) X-ray luminosity and the MIR luminosity: $\log L_{\text{MIR}} = (-4.37 \pm 3.08) + (1.106 \pm 0.071) \log L_{\text{X}},$ where $L_{\text{MIR}}$ is the monochromatic luminosity at 12.3 µm, in units of $L_{\odot}$, expressed in erg s$^{-1}$. This relation holds for both obscured and unobscured AGNs (Gandhi et al. 2009). We then subtract the corresponding flux density from the measured 24 µm one and re-compute the $q_{24\text{obs}}$ value, corrected for the AGN emission, for all our RQ AGNs in the redshift range 0.85 < $z$ < 1.15 (20 objects). We find that only one object would be classified as an RL AGN after the correction for the AGN emission of the $q_{24\text{obs}}$ value. Therefore, we can estimate that the contamination of the RL AGN population from RQ AGNs is $\approx 5$ per cent.

6.2 Host galaxy properties versus radio loudness

Focusing our attention on the AGN population, we can study the properties of AGN host galaxies as a function of radio loudness.

While we find that RL AGNs are preferentially hosted by high stellar mass galaxies, we do not observe a similar trend for RQ AGNs (Section 5.2). Both the morphology and the rest-frame optical colours show a clear separation between the two types of AGNs. RL AGNs are preferentially found in elliptical galaxies (Sérsic index $\sim$4), while RQ AGNs have usually lower Sérsic indices typical of late-type galaxies (Section 5.1). In Section 5.3, we computed the rest-frame optical colours from the results of the two-component (AGN+galaxy) SED fitting. We note that since the rest-frame colours are computed from the best-fitting galaxy template only, we minimize the contamination from the AGN emission itself (see Bongiorno et al. 2012 for a more detailed discussion). RL AGNs lie along the red sequence (see Fig. 10) suggesting that their host galaxies are old stellar population systems. If we look at the measured rest-frame $U-B$ colours, we observe that RQ AGNs have a wider range of colours but the red objects are more likely dusty systems rather than old stellar population objects. This appears more clearly when we consider the dust extinction-corrected colours (right-hand panel of Fig. 10); the intrinsic rest-frame optical colours of RQ AGNs are bluer compared to RL AGNs, implying the presence of young stars in the host galaxies of these AGNs. Also in the IRAC colour–colour diagram (Fig. 3), we see that RL AGNs are more concentrated in the bottom-left part of the diagram. Here, we expect to find passive systems, with a declining power-law behaviour across the four IRAC bands (see the elliptical colour–colour track in Fig. 3).

Given these differences in the host galaxy properties, we suggest that the RQ and RL activity occurs at two different evolutionary stages of the BH–host galaxy co-evolution. RQ AGNs are in an early phase, when the galaxy is gas rich, is still forming stars, has a young stellar population and the AGN is efficiently accreting. The radio activity of the AGN occurs instead at later times when the galaxy is gas poor, the accretion on the BH is inefficient, the star formation in the host decreases and the stars get older and redder.

RL AGNs can be further divided into high- and low-excitation sources (e.g. Laing et al. 1994; Hardcastle, Evans & Croston 2007; Baldi & Capetti 2008). The excitation level of a source is usually quantified using a combination of different line ratios (e.g. Best & Heckman 2012). Given the high redshift of our sample and the incomplete spectroscopic coverage, the excitation parameter can be computed only for very few (<10) RL AGNs. For these reasons, a detailed discussion about the excitation level of our RL AGNs goes beyond the scope of this paper. In Best & Heckman (2012), the host galaxy properties of high- and low-excitation RL AGNs have been compared. Low-excitation sources are found to have on average larger $D_{4000}$ and higher stellar masses compared to high-excitation sources. Our sample of RL AGNs spans the whole range of $D_{4000}$ found in the Best & Heckman (2012) sample suggesting that it is a mixture of low- and high-excitation sources. However, given the large uncertainties of our measurement of the 4000 Å break strength and the intrinsic large scatter in the $D_{4000}$ distribution for both low- and high-excitation sources, a quantitative estimate is not reliable. More recently, it has been found that it is possible to separate low- and high-excitation RL sources on the basis of their MIR luminosities (Gürkan, Hardcastle & Jarvis 2013). They propose an empirical 22 µm luminosity threshold of $5 \times 10^{42}$ erg s$^{-1}$ below which almost all the RL AGNs are low-excitation sources. We extrapolated the 22 µm luminosity from the source photometry. We find that about 85 per cent of the RL AGNs have MIR luminosity typical of low-excitation sources. However, this method has not yet been tested for a faint sample as the one presented in this paper. Therefore, this fraction can only be considered a tentative estimate. Finally, we note the all the studies conducted so far on the excitation level of radio sources have been applied only to RL AGN samples (e.g. Hardcastle et al. 2007; Baldi & Capetti 2008; Janssen et al. 2012; Gürkan et al. 2013). For a radio-selected sample of RQ AGNs, the distinction between low- and high-excitation sources would be difficult even having good quality optical spectra since the host galaxy can strongly contaminate the optical emission. Also the method based on the MIR luminosity cannot be applied as it assumes no contribution from young stars at 22 µm that is usually not true for the hosts of RQ AGNs. Even if RQ AGN host galaxies are more similar to the one of high-excitation sources (e.g. blue colours, small masses), direct measurements of their excitation state have not yet been conducted.
6.3 Radio emission in RQ AGNs

The origin of the radio emission in RQ AGNs has been debated for a long time. It has been suggested that RQ AGNs are a scaled version of RL AGNs at lower radio power (e.g. Miller, Rawlings & Saunders 1993) or that the major contribution to the radio emission in these systems is due to the star formation in the host galaxy (e.g. Sopp & Alexander 1991). In particular, in Padovani et al. (2011) the latter hypothesis was supported by the study of the cosmological evolution and luminosity function. They found that both are significantly different for the two types of AGNs, while they are indistinguishable for SFGs and RQ AGNs.

In this paper, we had characterized the host galaxy properties for the three types of sources. We find that the host galaxy of RQ AGNs and our radio-selected SFGs have many similarities. Both RQ AGNs and SFGs have luminosity profiles preferentially with low Sérsic indices (n < 2) suggesting that, on average, both have disc-like morphology. The rest-frame optical $U-B$ colours reveal that they are dusty, but intrinsically blue as seen from the comparison of the right- and left-hand panels of Fig. 10. These results support the hypothesis that the origin of the radio emission is related to the star formation processes in the host galaxies of both AGNs as proposed in Padovani et al. (2011) and Kimball et al. (2011). This will be further discussed in coming papers, where we will investigate the star formation activity in the host galaxies of our radio-selected RQ AGNs using Herschel data (Bonzini et al., in preparation). We will also study the luminosity function and evolution for the different population of the larger sample considered in this work (Padovani et al., in preparation) to be compared with the results of Padovani et al. (2011).

7 SUMMARY AND CONCLUSIONS

The sub-mJy radio population turns out to be a mixture of different kinds of sources due to the synchrotron emission from the relativistic particles accelerated either by the BH or associated with star formation processes.

In this work, we present a simple scheme, which expands upon that of Padovani et al. (2011), to disentangle the different populations of the sub-mJy radio sky: RL AGNs, RQ AGNs and SFGs. We have shown that the ratio between the radio and infrared emission, parametrized by the $q_{24obs}$ value, is the key parameter needed to identify RL AGNs. To differentiate between SFGs and RQ AGNs, it is instead necessary to consider other AGN activity indicators, namely the X-ray luminosity and the MIR observed colours. Classification methods based only on optical properties are inefficient in finding RQ AGNs since their emission can be dominated by the host galaxy or be heavily absorbed at these wavelengths. The simplicity of our scheme makes it suitable to be applied to large radio samples with ancillary X-ray and IR data, without the need of a spectroscopic follow-up.

We confirm the increasing predominance at lower flux densities of SFGs, which make up $\sim$60 per cent of our sample down to $\sim$32 $\mu$Jy and become the dominant radio population below $\sim$0.1 mJy. RQ AGNs are also confirmed to be an important class of sub-milliJansky sources, accounting for 26 per cent of the sample and $\sim$60 per cent of all AGNs, and outnumbering RL AGNs at $\lesssim$ 0.1 mJy.

We study the host galaxy properties of the three types of sources. Stellar masses and rest-frame optical colours of the galaxy are obtained using a two-component SED fitting technique (galaxy+AGN) that allows us to subtract the AGN contribution. Morphological properties are based on ACS/HST images. We observe differences in the host galaxy properties of RL and RQ AGNs both in the rest-frame optical colours and in the morphology. RL AGNs are preferentially hosted by more massive, red, elliptical galaxies, while RQ AGNs have typically stellar masses of $10^{10.5} M_\odot$, bluer colours and late-type morphology. This result is in agreement with what is found in previous works and supports our classification method. It also suggests that the radio activity associated with the BH is linked to the properties of the host galaxy. One possible scenario is that they represent two different evolutionary stages of the BH–galaxy evolution. In the RQ phase, the radio emission from the AGN is low or even absent and the galaxy is young and still forming stars. In a later stage, the radio activity of the AGN becomes more important as the galaxy gets older and stops forming stars.

Comparing our radio-selected SFGs and the host galaxies of RQ AGNs, we find many similarities. This result further supports the hypothesis that the radio emission in RQ AGNs predominately comes from the star formation processes in the host galaxy rather than from the BH activity, in agreement with Padovani et al. (2011) and Kimball et al. (2011). In an upcoming paper, we will discuss further this topic (Bonzini et al., in preparation). Based on this conclusion, we developed a powerful tool to disentangle the two radio emission mechanisms. Indeed, using the $q_{24obs}$ only, we can separate AGN-powered radio emitters from systems where radio emission comes mostly from star formation. This result can be applied to large radio samples such as the ones that existing and planned radio facilities will provide (e.g. Norris et al. 2013).

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Additional Supporting Information may be found in the online version of this article:

Table 1. Classification of radio sources (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1879/-/DC1).

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