The radio properties of optically obscured Spitzer sources

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\begin{abstract}
This paper analyses the radio properties of a subsample of optically obscured ($R \geq 25.5$) galaxies observed at 24\,$\mu$m by the Spitzer Space Telescope within the First Look Survey. 96 $F_{24\mu m} \geq 0.35$ mJy objects out of 510 are found to have a radio counterpart at 1.4 GHz, 610 MHz or at both frequencies respectively down to $\sim 40\mu$Jy and $\sim 200\mu$Jy. IRAC photometry sets the majority of them in the redshift interval $z \simeq [1–3]$ and allows for a broad distinction between AGN-dominated galaxies ($\sim 47\%$ of the radio-identified sample) and systems powered by intense star-formation ($\sim 13\%$), the remaining objects being impossible to classify. The percentage of radio identifications is a strong function of 24\,$\mu$m flux: almost all sources brighter than $F_{24\mu m} \sim 2$ mJy are endowed with a radio flux at both 1.4 GHz and 610 MHz, while this fraction drastically decreases by lowering the 24\,$\mu$m flux level. The radio number counts at both radio frequencies suggest that the physical process(es) responsible for radio activity in these objects have a common origin regardless of whether the source shows mid-IR emission compatible with being an obscured AGN or a star-forming galaxy. We also find that both candidate AGN and star-forming systems follow (although with a large scatter) the relationship between 1.4 GHz and 24\,$\mu$m fluxes reported by Appleton et al. (2004) which identifies sources undergoing intense star formation activity. However, a more scattered relation is observed between 24\,$\mu$m and 610 MHz fluxes. On the other hand, the inferred radio spectral indices $\alpha$ indicate that a large fraction of objects in our sample ($\sim 60\%$ of all galaxies with estimated $\alpha$) may belong to the population of Ultra Steep Spectrum (USS) Sources, typically 'frustrated' radio-loud AGN. We interpret our findings as a strong indication for concurrent AGN and star-forming activity, whereby the 1.4 GHz flux is of thermal origin, while that at 610 GHz mainly stems from the nuclear source.
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1 INTRODUCTION

The advent of the Spitzer Space Telescope has marked a fundamental milestone in our understanding of the assembly history of massive spheroidal galaxies, one of the major issues for galaxy formation models. The unprecedented sensitivity of the Multiband Imaging Photometer for Spitzer (MIPS) at 24\,$\mu$m has in fact for the first time allowed the detection at high redshifts of a population of Luminous and UltraLuminous Infrared Galaxies (LIRGs; ULIRGs) with huge infrared luminosities ($L_{IR} > 10^{11} L_{\odot}$). Such sources are underluminous at rest frame optical and UV wavelengths because they are reprocessing and radiating much of their energy in the IR (e.g. Sanders & Mirabel 1996). As a consequence, LIRGs and ULIRGs at high redshifts had been missed so far either due to their extreme optical faintness or because previous infrared missions such as the InfraRed Astronomical Satellite (IRAS) or the Infrared Space Observatory (ISO) did not have enough sensitivity to push the observations beyond $z \sim 1$.

Recent studies have shown that these objects, while relatively rare in the local universe (e.g. Sanders & Mirabel 1996), become an increasingly significant population at higher redshifts (e.g. Le Floch\textsuperscript{et al.} 2004; 2005; Lonsdale\textsuperscript{et al.} 2004; Caputi\textsuperscript{et al.} 2006; 2007) and likely dominate the luminosity density at $z > 1$ (see e.g. Dole\textsuperscript{et al.} 2006). Their space density, found to range between $10^{-3}$ and a few $10^{-2}$ Mpc\textsuperscript{-3} according to the selection criteria adopted by different studies (see e.g. Caputi\textsuperscript{et al.} 2007; Daddi\textsuperscript{et al.} 2007a, Magliocchetti\textsuperscript{et al.} 2007a), is a factor of 10 to 100 higher than that of optically selected quasars in the same redshift range (e.g. Porciani, Magliocchetti & Norberg 2004). Furthermore, clustering studies (e.g. Magliocchetti\textsuperscript{et al.} 2007a; 2007a; Farrah\textsuperscript{et al.} 2006) prove that, at variance with their local counterparts, LIRGs and ULIRGs at $z \sim 2$ are associated with extremely massive ($M \gtrsim 10^{13} M_{\odot}$, where $M$ here refers to the dark matter) structures, only second to those which locally host very rich clusters of galaxies. Given their properties, it then appears clear that these sources represent a fundamental phase in the build up of massive galactic bulges, and in the growth of their supermassive black holes.
Emission line diagnostics for bright \( F_{24\mu m} \gtrsim 1 \) mJy mid-IR samples of LIRGs and ULIRGs at \( z \sim 2 \) in the near and mid-IR spectral regimes (see e.g. Yan et al. 2005; 2007; Weedman et al. 2006; 2006a; Brand et al. 2007; Martínez-Sansigre et al. 2006a) have shown these sources to be a mixture of obscured type1-type2 AGN and systems undergoing intense star formation activity. These findings are confirmed by photometric follow up mainly undertaken in the mid-IR and X-ray (both soft and hard) bands which also prove that the fraction of galaxies dominated by a contribution of AGN origin is drastically reduced at faint mid-IR fluxes (e.g. Brand et al. 2006; Weedman et al. 2006; Treister et al. 2006; Magliocchetti et al. 2007). Unfortunately, the exact proportion of AGN vs starforming dominated galaxies is still undetermined. This separation is further complicated by the existence of a noticeable number of mixed systems where both star formation and AGN activity significantly contribute to the IR emission. For instance, Daddi et al. (2007a) find that about 20\% of 24\mu m-selected galaxies in the GOODS sample show a mid-IR excess which is not possible to reconcile with pure star-forming activity. Such a fraction increases to \( \sim 50 - 60\% \) at the highest (stellar) masses probed by their study.

Clearly, understanding how the mid-IR sources divide between starbursts, AGN and composite systems is now the next essential step in order understand the relationships amongst the formation and evolution of stars, galaxies and massive black holes powering AGNs within dusty environments and more generally within massive systems observed at the peak of their activity.

This paper approaches the study of the population of optically faint luminous infrared galaxies from the point of view of their multifrequency radio emission. Diagnostics based on the radio signal stemming from these sources can in fact provide precious information on the processes which are actively taking place within such systems. Enhanced radio activity can stem from supernova remnants associated with regions which are vigorously forming stars, or originate from nuclear activity (AGN-dominated sources). These two processes determine a rather different spectral behaviour at radio wavelengths: star-forming systems are in general characterized by radio spectra which feature power-law shapes with slope (hereafter called radio spectral index \( \alpha \), defined as \( F \propto \nu^{-\alpha} \), with \( F \) radio flux and \( \nu \) radio frequency) of the order of \( \sim 0.7-0.8 \), while typical radio-loud quasars exhibit values for \( \alpha \) between 0 and 0.5 even though, especially at high redshifts, there is a non negligible population of radio-loud sources with very high, \( \alpha > 1 \), values (see e.g. De Breuck et al. 2000).

Radio counterparts to the 510 optically faint mid-IR selected sources drawn from the whole First Look Survey sample (Fadda et al. 2006) have been searched in the overlapping region between MIPS and IRAC observations (Magliocchetti et al. 2007). Despite not having direct redshift estimates except for a handful of cases (e.g. Weedman et al. 2006; Yan et al. 2005; 2007; Martínez-Sansigre et al. 2006a), mid-IR photometry indicates that the overwhelming majority of such sources reside at redshifts \( 1.7 \lesssim z \lesssim 2.5 \) (§ 4; see also Brand et al. 2007; Houck et al. 2005; Weedman et al. 2006a).

The First Look Survey region provides an excellent laboratory for investigations of the radio properties of dusty galaxies set at redshifts \( z \sim 2 \) as its area has been observed at a number of radio frequencies down to very low flux densities (Condon et al. 2003; Morganti et al. 2004; Garn et al. 2007), therefore maximizing our chances of finding radio emitting galaxies.

The layout of the paper is as follows. In §2 we introduce the parent (mid-IR and radio) catalogues, while in §3 we present the matching procedure leading to the sample of optically obscured Spitzer-selected sources with a radio counterpart at 1.4 GHz and/or 610 MHz. §4 uses IRAC photometry to provide some information on the typology of such objects (i.e. whether mainly powered by an obscured AGN or by a starburst) and also – where possible – to assign them to a redshift interval. §5 presents the results on the radio number counts both at 1.4 GHz and 610 MHz (§5.1) and on the relationship between radio and 24\mu m emission (§5.2). §6 discusses our findings on the 1.4 GHz vs 610 MHz radio spectral indices for the objects in our sample, while §7 summarizes our conclusions.

## 2 Parent Catalogues

### 2.1 Optically Obscured Spitzer Sources

The primary selection of the sources in this work comes from Spitzer-MIPS 24\mu m observations of the \( \sim 4 \) square degrees region denoted as First-Look Survey (FLS, Fadda et al. 2006). Out of the original parent catalogue, in the 2.85 square degrees area covered by both MIPS and IRAC (Lacy et al. 2005) data, Magliocchetti et al. (2007) selected sources with 24\mu m fluxes brighter than 0.35 mJy, limit which ensures \( \sim 100\% \) completeness of the MIPS dataset. As a further, crucial selection, Magliocchetti et al. (2007) required the above objects to be optically obscured. In practical terms, the requirement was that these sources had to be fainter than \( R \sim 25.5 \) (i.e. undetected) in the KPNO catalogue (Fadda et al. 2004) which covers the entire FLS region. As indicated by colour-colour evolutionary tracks for a number of known templates (see e.g. Figure 2 of the Magliocchetti et al. 2007 paper), and recently confirmed by results based on both mid-IR and near-IR spectroscopy, the above constraint forces the overwhelming majority of these objects to reside at redshifts beyond \( z \sim 1.6 \), with an average of \( z \sim 2 \) (see e.g. Weedman et al. 2006; Yan et al. 2005; 2007; Brand et al. 2007). The final number of obscured, \( F_{24\mu m} \gtrsim 0.35 \) mJy, galaxies in the overlapping MIPS-IRAC region is 510. Diagnostics based on the 8\mu m/24\mu m flux density ratios indicate that these are a mixture of galaxies undergoing an extreme event of stellar formation and obscured AGN, this latter population dominating at bright, \( F_{24\mu m} \gtrsim 0.8 \) mJy fluxes (see also Brand et al. 2006; Treister et al. 2006).

The distribution of all the 510 optically obscured, 24\mu m-selected sources as obtained by Magliocchetti et al. (2007) is represented by the open (red) circles in Figure 1.

### 2.2 The Radio Catalogues

The whole FLS region was observed at 1.4 GHz by Condon et al. (2003). They used the B configuration of the VLA to obtain radio images with \( \sigma_F \sim 23 \mu\text{Jy beam}^{-1} \) rms fluctuations, \( \theta = 5'' \) resolution and a positional rms of about 0.5
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Figure 1. Sky distribution of sources in the FLS area. The (blue) squares are radio objects from the 610 MHz GMRT observations (Garn et al. 2007), the (green) triangles are the 1.4 GHz Morganti et al. (2004) sources, while the (red) open circles are the 510, 24µm-selected sources brighter than 0.35 mJy without an optical counterpart brighter than $R \simeq 25.5$ coming from the Magliocchetti et al. (2007) sample (see text for detail).

Figure 2. 1.4 GHz differential number counts for the Morganti et al. (2004) sample in $\Delta F_{1.4\GHz} = 0.02$ mJy bin widths. The vertical dotted line represents the estimated limit for completeness, while the dashed line is the best-fit to the data for fluxes $F_{1.4\GHz} \geq 80\mu Jy$.

Figure 3. 610 MHz differential counts from the GMRT Survey (Garn et al. 2007) in $\Delta F_{610\MHz} = 0.1$ mJy bin widths. The vertical dotted line represents the limit for completeness, while the dashed line is the best-fit to the data for $F_{610\MHz} \geq 0.4$ mJy.
of these sources is presented in Figure 1 by the (blue) filled squares.

The differential number counts as a function of 610 MHz integrated flux density for the Garn et al. (2007) sample is plotted in Figure 2 for a bin width $\Delta F_{610\text{MHz}} = 0.1$ mJy. The sample includes sources brighter than $~0.1$ mJy, with a $\sim 5\sigma$ level for completeness reached for fluxes $F_{610\text{MHz}} > 400\mu$Jy. The best fit to the complete part of the dataset only, represented in Figure 3 by the dashed line, is provided by the expression $N(F_{610\text{MHz}}) = A' F_{610\text{MHz}}$, with $A' = 98 \pm 11$ and $\gamma' = 2.0^{+0.1}_{-0.2}$.

3 THE MATCHED SAMPLE

Radio counterparts to optically obscured Spitzer sources were searched by cross-correlating the catalogue obtained by Magliocchetti et al. (2007) and described in §2.1, with those provided by Condon et al. (2003), Morganti et al. (2004) and Garn et al. (2007).

Given the large resolution beam associated to the Morganti et al. (2004) observations, in order to provide a self-consistent searching radius at both 1.4 GHz and 610 MHz, as a first step we have decided to consider as true radio counterparts 24\mu m-selected, $R > 25.5$ sources radio objects whose positions differed from those of MIPS galaxies by less than $10''$. 53 matches out of 510 sources (corresponding to 10.4% of the original Spitzer sample) were found in the case of the 610 MHz GMRT Survey over the whole FLS-IRAC area. On the smaller region covered by the Morganti et al. (2004) observations, we instead find 33 matches out of 150 optically obscured Spitzer sources which occupy the same portion of the sky. This corresponds to $\sim 22\%$ of the original sample.

The chances for contamination both in the case of 1.4 GHz and for 610 MHz observations have been estimated by shifting in both RA and Dec the Spitzer sample with respect to the radio ones. This was repeated ten times for different shifting amounts which ranged between 1 and 5 arcminutes. The resulting values for chance coincidences were then averaged. By doing this, for the Morganti et al. (2004) dataset we expect $\sim 12$ spurious matches, while in the GMRT case this figure rises to 7 objects. These values are somewhat lower than what statistically predicted by considering the surface density of both radio and MIPS sources: for the 610 MHz sample we expect $\sim 12$ spurious matches, while for the Morganti et al. (2004) sample this figure is $\sim 4$. One possible explanation for such a discrepancy could be found in the non-uniform coverage of both the Garn et al. (2007) and Morganti et al. (2004) surveys (§2.2). As a matter of fact, there are only 6 sources with an offset between 610 MHz and 24\mu m positions greater than 6 arcsec, size of the GMRT beam and radius at which the chances for contamination drop to $\lesssim 4\%$. They are: J171948.6+585133, J171810.7+591639, J172317.5+591109, J171628.4+601342, J172122.3+600605, J172042.6+500930. These objects have been checked by eye on the 1.4 GHz maps provided online by Condon et al. (2003; url: http://www.cv.nrao.edu/sirtf/) and in all cases they were found to likely be real associations.

Finally, we also used the Condon et al. (2003) catalogue provided online and searched for 1.4 GHz counterparts to optically obscured Spitzer galaxies within the same matching radius of $10''$ as indicated above over the whole FLS-IRAC region. The number of sources with measured radio fluxes from the Condon et al. (2003) online catalogue is 70, corresponding to $13.7\%$ of the original sample. Also in this case we have visually checked those radio-to-24\mu m associations having distances between 6'' and 10'' and found them to likely be real ones. These objects are: J171529.9+593448, J171656.7+594103, J172317.5+591109, J171511.5+585741, J172050.3+590638, J172050.3+592430 and J172042.6+590930.

Figure 4. 1.4 GHz integrated flux densities for the optically obscured Spitzer sources presented in this work as reported by Morganti et al. (2004; y-axis) and Condon et al. (2003; x-axis) in the portion of sky where these two surveys overlap (green circles). The small dots represent the Condon et al. (2003) and Morganti et al. (2004) flux measurements for all radio sources which appear in both catalogues.

Fifteen sources belonging to the original $R > 25.5$, Spitzer sample have 1.4 GHz counterparts both in the Condon et al. (2003) and Morganti et al. (2004) catalogues. A comparison of their integrated radio fluxes (performed in Figure 2) as taken from these two datasets, shows that – except for a few cases – the Morganti et al. (2004) fluxes are systematically lower than those measured by Condon et al. (2003). We do not know the reason for this discrepancy which, given the larger beam of the WSRT, if anything should have gone the other way round (i.e. Condon fluxes smaller than the Morganti et al. ones). A possible cause could be found in calibration problems which may have affected flux measurements for faint sources in one or another survey. The same trend for fluxes as coming from the Morganti et al. (2004) catalogue to be systematically lower than those measured by Condon et al. (2003) is in fact observed for all radio sources fainter than $\sim 1$ mJy which are present in both datasets (520 to a distance of 6 arcsec; see Figure 4).

For the 15 Spitzer sources belonging to our sample with double 1.4 GHz measurements, we then decided to adopt as ‘true’ fluxes those given by Condon et al. (2003) as it is in this sample where we find the overwhelming major-
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Figure 5. Left-hand panel: fractional number of 1.4 GHz counterparts to obscured Spitzer sources as a function of 24\,\mu m flux. The (green) squares are for the Condon et al. (2003) sample, while the (red) dots are for the Morganti et al. (2004) dataset. Error-bars represent the 1\sigma Poisson uncertainties on the number of sources. Right-hand panel: same as before but for the GMRT survey (Garn et al. 2007).

ity of 1.4 GHz counterparts to our Spitzer sources. We note that most of the following analysis and discussion, especially that devoted to the radio spectral indices in \S6, is only very marginally affected by the eventual inclusion of the information coming from the Morganti et al. (2004) dataset.

Out of the remaining 18 optically faint Spitzer objects with counterparts in the Morganti et al (2004) catalogue, 16 of them have radio fluxes smaller than \sim 130\,\mu Jy, consistent with the fact that we do not find them in the Condon et al. (2003) dataset. However, two objects, quite bright in the Morganti et al. (2004) radio maps did not seem to have been included in the Condon et al. (2003) catalogue. These are J171427.8+592828 (F_{\text{1.4GHz}} = 0.83\,\text{mJy}) and J171527.5+593139 (F_{\text{1.4GHz}} = 0.39\,\text{mJy}). Direct visual investigations of the radio maps provided online by Condon et al. (2003) show that in the first case the source has been missed in the matching procedure with the Condon et al. (2003) catalogue as presenting a distance between radio and Spitzer counterpart greater than the adopted 10\arcsec matching radius. The association however looks real, as the 24\,\mu m emission comes from a lateral blob of the radio source (see the postage stamp in the middle of the bottom row in Figure 15). Also J171527.5+593139 exists in the Condon et al. (2003) radio maps, even though they measure a 1.4 GHz radio flux which is faint enough to have it excluded from their > 5\sigma_{\text{F}} catalogue. We therefore also take this radio-to-Spitzer association as real, even though we warn the reader on the reliability of its 1.4 GHz flux value.

Finally, with the help of the higher positional accuracies and smaller beam resolutions of the Condon and IRAC surveys with respect to those of the 24\,\mu m MIPS channel (see \S2.2 and \S4), we find that there were three objects in the radio-Spitzer catalogue which were erroneously split into a number of different sources. These are J171628.4+601342, which the deconvolution technique adopted for MIPS sources had divided into three different objects, and J172018.1+592902 and J172353.2+601354, which both appear in the original Spitzer catalogue as two different objects. However, all of them only had one identification at both 1.4 GHz and in the IRAC channels. In these cases, the 24\,\mu m flux associated to the single Spitzer source was simply obtained by adding the 24\,\mu m fluxes of its sub-components.

The result of the above ‘cleaning procedures’ leaves 67 radio identified optically faint Spitzer sources from the Condon et al. (2003) catalogue, 17 from the Morganti et al. (2004) catalogue and 52 from the Garn et al. (2007) dataset. To this last figure we have also added 5 more sources (i.e. J171054.4+594426, J172005.0+592430, J172103.6+585052, J171427.8+592828, J172217.4+601003) which had bright (F_{\text{1.4GHz}} \gtrsim 0.8\,\text{mJy}) 1.4 GHz counterparts but no measured 610 MHz fluxes from the automatic matching procedure. Visual investigations of the radio maps have in fact shown that in all but one of these five 1.4 GHz-identified sources – the radio emission is extended and the 24\,\mu m signal stems from regions which correspond to secondary peaks in the radio emission. This explains the 610 MHz-to-24\,\mu m association to be found at distances slightly larger than 10\arcsec. Images for these four cases are presented in Figure 15 (top-left, top-right, centre and bottom-centre), while all the five sources are furtherly discussed in the Appendix.

The final number of optically faint Spitzer sources with a radio counterpart either at 1.4 GHz or at 610 MHz or at both frequencies is 96. This is the sample which we will use for our studies throughout the paper. All these sources were visually checked in the Condon et al. (2003) radio maps to assess the likelihood of the associations, investigate peculiarities in the radio-to-24\,\mu m emission and look for interesting features in their radio morphologies. Except for one dubi-
ous case (namely J172217.4+601003), all the other radio-to-24µm associations look real.

The mid-IR and radio properties for these sources are summarized in Table 1. The Appendix instead provides images and a more detailed description for the most peculiar objects. Except for J171143.9+600741 and J172005.0+592430 which are two very extended and bright triple sources, in all the other cases of (more dubious) multicomponents, the radio fluxes reported in Table 1 and used throughout this work simply correspond to the flux of the radio source which is closest to the centre of 24µm emission, i.e. no collapsing technique has been applied to these objects. However, images and a detailed description for all of them are given in the Appendix. In passing, we note that in most of the brightest radio sources (i.e. brighter than $F_{1.4GHz} \sim 0.8$ mJy, see Figure 15), the mid-IR emitting region is associated to secondary peaks of radio emission such as radio lobes and jets or distant star-forming regions rather than stemming from the site of primary radio emission, most likely corresponding to the position of the accreting black hole. If these associations are indeed real, they surely deserve a deeper investigation which will be the subject of a forthcoming paper.

The fraction of radio-identified/optically obscured Spitzer sources as a function of 24µm flux is shown in Figure 5 left-hand panel for what concerns 1.4 GHz observations and right-hand panel for 610 MHz ones. In the left-hand panel, (green) squares correspond to the Condon et al. (2003) data, while the (red) dots are for the Morganti et al. (2004) measurements. Almost all the sources with 24µm fluxes brighter than $\sim 2$ mJy have been identified at 1.4 GHz. In more detail, we have that only one object brighter than the above limit does not have a 1.4 GHz counterpart either in the Morganti et al. (2004) or in the Condon et al. (2003) catalogues (see also Figure 10). However, such a high completeness level for radio identifications quickly drops as one moves to fainter 24µm fluxes, especially if the radio counterpart is searched for within radio objects brighter than $F_{1.4GHz} \sim 0.1$ mJy as it is the case for the Condon et al. (2003) data. The fraction of radio-identified Spitzer sources instead remains quite high (on the order of 50%) at all $F_{24\mu m} \gtrsim 0.5$ mJy fluxes if one considers objects with 1.4 GHz fluxes below $\sim 0.1$ mJy as those probed by the Morganti et al. (2004) survey.

The situation is quite different if one considers the case for 610 MHz counterparts to optically obscured Spitzer sources. In fact, due to the higher flux limit of the GMRT survey with respect to the 1.4 GHz ones, the fraction of radio-identified objects here is much lower, less than 50% even at the highest 24µm fluxes (see Figure 5). This fraction then dramatically drops to less than 20% already below $F_{24\mu m} \sim 1$ mJy.

4 IRAC PHOTOMETRY

As already mentioned in §2.1, the FLS area is covered by IRAC observations performed at 3.6, 4.5, 5.8 and 8µm. To look for IRAC counterparts to the optically faint sources presented in §2.1, we have then relied on the band-merged catalogue provided by Lacy et al. (2005) and cross-correlated

![Figure 6. IRAC fluxes for R > 25.5 Spitzer sources fainter than $F_{24\mu m} = 0.5$ mJy and belonging to our radio-identified sample (green squares). The solid line represents an Arp220-like SED redshifted at $z = 2$, while the dashed and dotted lines are for two Mkn231-like SEDs at $z = 2$ with different 24µm normalizations (0.5 mJy for the upper curve, 0.35 mJy for the lower one). The horizontal (magenta) dashes indicate the 5σ flux limits of the IRAC and MIPS data on the FLS area.](image-url)
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Figure 7. Distribution of $F_{3.6 \mu m}/F_{4.5 \mu m}$ vs $F_{24 \mu m}/F_{3.6 \mu m}$ flux ratios for those 57 radio-detected, optically faint Spitzer-FLS sources which present an IRAC counterpart at both 3.6 $\mu$m and 4.5 $\mu$m. These are compared with the computed colour-colour tracks as a function of redshift for four SEDs: that of Arp220 (magenta/dashed line), that of M82 (lower blue/dotted line), that of a Mkn231-like galaxy with an added evolved stellar contribution (upper blue/dotted line) and that of M51 (cyan short/long dashes). Some reference redshift values are marked by crosses (example of a Mkn231-like galaxy with an added evolved stellar contribution). The radio-identified sources (i.e. whether AGN0, AGN1, SB0, SB1 or LI) are reported in Table 1. The three dubious cases of AGN1; $F_{24 \mu m}/F_{3.6 \mu m} < 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} \geq 0.1$; 94 objects. The addition of the two lowest wavelength IRAC channels can also help us finding low redshift contaminants. To this aim, the distribution of $F_{3.6 \mu m}/F_{4.5 \mu m}$ vs $F_{24 \mu m}/F_{3.6 \mu m}$ colours for the whole sample of optically obscured Spitzer sources with $F_{24 \mu m} \leq 0.5$ mJy have then been classified as AGNs if $F_{4.5 \mu m}/F_{3.6 \mu m} \geq 4.5/3.6$. All the other objects, with either no available IRAC photometry or with $F_{4.5 \mu m}/F_{3.6 \mu m}$ ratios shallower than the adopted value are instead to be considered as unclassified since an evolved stellar population could be present in both star-forming galaxies and AGN-dominated systems.

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The above analysis, together with the results presented in Magliocchetti et al. 2007, allows to identify the following categories for 24$\mu$m-selected sources without an optical counterpart:

A) Parent MIPS-IRAC catalogue (510 sources):
- AGN0: $F_{24 \mu m} \geq 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} \geq 0.1$; 104 objects.
- SB0: $F_{24 \mu m} \geq 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} < 0.1$; 31 objects.
- AGN1; $F_{24 \mu m} < 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} \geq 4.5/3.6$; 117 objects.
- Unclassified; $F_{24 \mu m} < 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} < 4.5/3.6$ or no IRAC information; 258 objects.

B) Radio-identified catalogue (96 sources):
- AGN0; $F_{24 \mu m} \geq 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} \geq 0.1$; 29 objects.
- SB0; $F_{24 \mu m} \geq 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} < 0.1$; 13 objects.
- AGN1; $F_{24 \mu m} < 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} \geq 4.5/3.6$; 16 objects.
- Unclassified; $F_{24 \mu m} < 0.6$; $F_{3.6 \mu m}/F_{24 \mu m} < 4.5/3.6$ or no IRAC information; 33 objects.

The distribution of $F_{3.6 \mu m}/F_{4.5 \mu m}$ vs $F_{24 \mu m}/F_{3.6 \mu m}$ colours for the subsample of radio-identified sources is presented in Figure 7. Open circles are for the subclass of AGN0, while filled ones for AGN1. We note that in the subsample of radio-identified sources there are five low-z contaminants (i.e. $z \leq 0.5$ galaxies most likely of the M51-type, hereafter denoted as local interlopers or LI). These sources, unless explicitly stated, will never be included in the following analysis and discussions. We also note that there are three dubious cases of $z \leq 1$ sources, which were also classified as AGN on the basis of their $F_{24 \mu m}/F_{3.6 \mu m}$ ratios but which could also possibly be M82-like galaxies. The various classes for the radio-identified sources (i.e. whether AGN0, AGN1, SB0, UNCL or LI) are reported in Table 1. The three dubious AGN cases are denoted with an ‘AGN0?’

IRAC photometry can also be used to provide rough redshift estimates. In fact, Magliocchetti et al. (2007) could only perform a very broad distinction between local Spitzer sources and high redshift (i.e. $z \geq 1.6$) ones based on comparisons between 24$\mu$m-vs-R colours and computed colour-colour evolution tracks obtained for a number of representative dusty SEDs such as Arp220 and Mkn231. Even though an indirect confirmation that at least the majority of such sources were indeed at high redshifts came from comparisons of the observed number counts with predictions from models for galaxy formation and evolution (e.g. Granato et al. 2004), the approach adopted by Magliocchetti et al. (2007) could only be considered as a zero-order one. As already noticed in the previous discussion, chances for contamination in the high-z sample are in fact non-negligible, especially in the case of obscured AGN which present power-law SEDs in the mid-IR region and are therefore more difficult to locate in redshift.

By making use once again of the colour-colour evolutionary tracks indicated in Figure 7, we can attempt at assigning broad redshift groups to all those sources belonging to the Magliocchetti et al. (2007) sample whose SEDs present a contribution from an evolved stellar population in the two 3.6$\mu$m and 4.5$\mu$m bands. In fact, as Figure 7 shows,
this method is quite robust, as - for a chosen (wide) redshift interval – all the adopted SEDs present similar values for the colours in the [3.6-4.5]μm range. The results of this analysis can be summarized as follows:

- z-type 1 (0 ≤ z ≤ 1): 52 (total sample), 11 (radio-id sample);
- z-type 2 (1 ≤ z ≤ 1.5): 36 (total sample), 7 (radio-id sample);
- z-type 3 (1.5 ≤ z ≤ 3): 54 (total sample), 13 (radio-id sample);
- z-type 4 (pure β > 1 PL AGN SED; no redshift assignment is possible in these cases): 111 (total sample), 27 (radio-id sample).

and show, as expected, that the majority of optically obscured Spitzer sources resides at redshifts ≥ 1 (∼ 65% of the sub-class of galaxies with assigned redshift), both for the whole population of optically faint Spitzer-selected sources and for the radio-identified ones. Perhaps not surprising, we have that almost all the sources at 1.4 GHz and for the radio-identified ones. Perhaps not surprising, we have that almost all the sources at 1.4 GHz and 610 MHz are in the right quadrant of Figure 7: this happens for stars > z 1.7 redshift range (see Figure 6). The inclusion of these sources in the next sections when we will investigate the nature of radio emission in these sources.

It is also interesting to notice that a significant portion of those objects classified as AGN-dominated present an evolved stellar population (circles which occupy the lower-right quadrant of Figure 7): this happens for 1.6 – 2.7 redshift range because of the characteristic rest-frame 8μm PAH region of their spectra (see Figure 6). The inclusion of these sources is then definitely expected to boost the fraction of z ≥ 1 sources as found in this Section by a sensible amount.

5 RADIO PROPERTIES

5.1 Number Counts

Figures 8 and 9 show the total number counts, while the right-hand ones illustrate the counts for the different categories, i.e. whether the source is to be considered an AGN, a star-forming galaxy or is unclassified. The different classifications, based on mid-IR photometry, come from §4 and the class of AGN includes all the sources denoted as both AGN0 and AGN1.

Two main features can be noticed from these plots. The first one is that the radio counts, both at 1.4 GHz and at 610 MHz of sources classified as star-forming galaxies and AGN are similar at all radio fluxes, especially if one adds together the ΔN/ΔF contributions coming from star-forming galaxies and unclassified objects. Indeed, as already observed in §2.1, IRAC observations which are deeper than those taken on the FLS show that the population which dominates the faint 24μm counts – in our case constituting the bulk of what we call the class of unidentified objects – is made of star-forming galaxies (see e.g. Brand et al. 2006; Weedman et al. 2006; Treister et al. 2006; Magliocchetti et al. 2007a). This similarity between the radio counts of star-forming objects and AGN at both radio frequencies is in striking disagreement with the results coming from mid-IR photometry which show a great discrepancy e.g. in the differential 24μm counts of these two classes of sources, whereby candidate AGNs constitute the preponderant population at bright fluxes, while – as discussed above – star-forming objects dominate the faint counts (see Figure 4 of Magliocchetti et al. 2007).

Although one cannot exclude some kind of cosmic conspiracy, such a similarity between the radio counts of star-forming galaxies and AGNs suggests that the origin(s) of the radio signal at the chosen frequencies is the same for both classes of objects. We will investigate this issue further in the next sections.

Some more information on the nature of radio emission in these sources can be provided by comparing the total (i.e. obtained for all the radio-identified objects, independent on their class) differential number counts at the different radio frequencies. A χ²-analysis performed on the 1.4 GHz counts for fluxes above the inferred completeness level (§2.2), shows that the best description to the data is provided by a functional form of the kind N(F) = ASF_1.4GHz^−γ_S, with AS = 1.0±0.2 and γ_S = 2.1±0.2. A similar approach applied to the 610 MHz-detected sample instead brings AS′ = 6.8±1 and γ_S′ = 2.0±0.6.

The slopes of the radio counts of optically obscured Spitzer sources at both 1.4 GHz and 610 MHz are in remarkable agreement with those found for the parent radio catalogues of Morganti et al. (2004) and Garm et al. (2007) (see §2 and Figures 2, and 3). If one again excludes some kind of cosmic conspiracy, this finding suggests that the class of radio-emitting objects set at redshifts z ~ 2 and with an enhanced mid-IR emission might not be too dissimilar from the population which dominates the (global) faint radio counts.

A direct comparison between the amplitudes AS and AS′ as obtained above for the radio counts of optically obscured sources at 1.4 GHz and 610 MHz and renormalized so to account for the different flux intervals adopted in estimating ΔN/ΔF at the two radio frequencies (ΔF_1.4GHz = 0.1 mJy and the data coming from the Morganti et al. (2004) catalogue have also been corrected so to take into account the smaller area covered by the survey. The left-hand panels of both Figures 8 and 9 show the total number counts, while the right-hand ones illustrate the counts for the different categories, i.e. whether the source is to be considered an AGN, a star-forming galaxy or is unclassified. The different classifications, based on mid-IR photometry, come from §4 and the class of AGN includes all the sources denoted as both AGN0 and AGN1.
Figure 8. Fractional number of obscured Spitzer sources with a radio counterpart vs 1.4 GHz flux. On the left-hand panel we report the total counts, while the plot on the right-hand side shows the counts as obtained for different types of objects: (red) circles are for AGN, (green) squares for star-forming galaxies and (blue) triangles for un-classified objects. Open symbols correspond to the Condon et al. (2003) radio measurements, filled ones to the Morganti et al. (2004) dataset. The dotted lines indicate the limit for 1.4 GHz radio completeness, while the dashed line in the left-hand plot is the best fit to the data beyond such a limit.

Figure 9. Fractional number of obscured Spitzer sources with a radio counterpart vs 610 MHz flux. On the left-hand panel we report the total counts, while the plot on the right-hand side shows the counts as obtained for different types of objects: (red) circles are for AGN, (green) squares for star-forming galaxies and (blue) triangles for un-classified objects. The long-short dashed lines indicate the limit for GMRT radio completeness, while the dashed line in the left-hand plot is the best fit to the data beyond such a limit.

in one case and $\Delta F_{610\,\text{MHz}} = 0.2$ mJy in the second case) and for the different total number of sources with a radio identification in the 1.4 GHz and 610 MHz catalogues, shows that the amplitude as inferred from the 610 MHz counts is about a factor two higher than that derived from the counts at 1.4 GHz ($156^{+26}_{-21}$ in the first case to be compared with $71^{+14}_{-21}$). If in the radio interval probed by the present observations we consider a SED for these sources which goes as a power-law of index $\alpha$ (the so-called radio spectral index, whereby we use the notation $F_R \propto \nu_R^{-\alpha}$, with $F_R$ radio flux and $\nu_R$ generic radio frequency), we can then see that such a factor two of discrepancy can only be reconciled if the sources present an average radio spectral index $\langle \alpha \rangle \sim 1$. Values of the order of $\langle \alpha \rangle = 0$ are strongly disfavoured by
Figure 10. Left-hand panel: 1.4 GHz vs 24 µm fluxes for optically obscured Spitzer sources. (Red) circles are for objects classified as AGN, (green) squares for candidate star-forming galaxies, (blue) triangles for unclassified sources and (magenta) stars for low-z interlopers. Crosses indicate those objects whose radio activity is most likely associated to a radio-loud AGN (see text for details). The upper set of arrows represents the radio upper limits for those Spitzer sources in the Magliocchetti et al. (2007) sample without a radio counterpart in the Condon et al. (2003) catalogue, while the lower set of arrows corresponds to sources without a 1.4 GHz counterpart also in the Morganti et al. (2004) dataset. The dashed line is the best fit to the Appleton et al. (2004) data. Right-hand panel: as before but for 610 MHz radio fluxes. The dashed line still represents the Appleton et al. (2004) results, while the dotted line is the Appleton et al. (2004) best-fit as converted to 610 MHz fluxes by assuming an average radio spectral index for the sources $\langle \alpha \rangle = 2$.

the data and this implies that the majority of our radio-identified Spitzer sources cannot be made of 'classical' flat-spectrum AGN.

5.2 Mid-IR vs radio emission

In §5.1, investigations of the radio number counts of $z \sim 2$, mid-IR-selected sources have shown that these objects are probably not too different from the population which dominates the total (relatively faint) radio counts at both 1.4 GHz and 610 MHz. Furthermore, we have found that it is likely that radio emission in these Spitzer sources originates from similar processes, regardless of whether the mid-IR SEDs identify them as AGN-dominated or powered by an intense event of stellar formation. Finally, we could exclude 'classical' flat-spectrum AGN as the typical object which constitutes our radio-identified sample, as a comparison between radio counts at 1.4 GHz and 610 MHz requires average radio spectral indices $\langle \alpha \rangle \sim 1$.

More information on the nature of radio emission for the sources included in our sample can be obtained from a direct comparison of mid-IR and radio emission. A tight correlation between far-infrared and radio emission from galaxies has in fact been observed for over three decades, since the pioneering works of e.g. Condon et al. (1982) based on very small samples of galaxies. The origin of this correlation is thought to lie in the link between massive stars, which generate infrared emission by reheating dust, and supernovae, which accelerate cosmic rays that generate radio synchrotron radiation (see e.g. Harwit & Pacini 1975; Condon 1992).

Observations with the InfraRed Astronomical Satellite (IRAS; Dickey & Salpeter 1984; de Jong et al. 1985; Condon & Broderick 1986) conclusively established such a correlation over a broad range of Hubble types and luminosities, from rich dwarfs to ultraluminous infrared galaxies at least in the local universe ($z \lesssim 0.1$). The advent of the Infrared Space Observatory (ISO) could for the first time probe the relatively higher-z universe, and it was found that even at 15 µm there was a loose correlation between mid-IR emission and the radio continuum (e.g. Cohen et al. 2000; Gruppioni et al. 2003). More recently, works based on data obtained with the Spitzer Space Telescope have proved the IR-radio correlation in starforming galaxies to hold both at 70 µm and - although with a larger dispersion - also at 24 µm at least to redshifts $\sim 1$, and possibly to $z \sim 2$ if one relies on stacking methods (e.g. Appleton et al. 2004; Norris et al. 2006; Boyle et al. 2007).

The 24 µm flux as a function of radio flux both at 1.4 GHz and at 610 MHz for the sources in our sample is reported in Figure 11. (Red) circles indicate those objects which are classified as AGN on the basis of their mid-IR photometry (where we put together the classes of AGN0 and AGN1, see §4), while (green) squares represent candidate starburst galaxies and (blue) triangles unclassified sources. The (few) low-z interlopers are marked by (magenta) stars. We cross out those objects which are doubtful associations (i.e. J172217.4+601003) and also those sources (namely J171054.4+594426, J171143.9+600741, J172005.0+592430, J171527.1+585802, J172103.6+585052, J171427.8+592828, J171417.6+600531, J171312.0+600840, J172305.1+593841, J172256.4+590053, J171948.6+585133, J172258.9+593126, J171239.2+591350) which, on the basis of their morphology...
likely belong to the class of radio-loud AGN, not observed to follow the mid-IR/radio correlation (see the Appendix for more details on these objects). The dashed lines in both panels represent the relationship found by Appleton et al. (2004) ($q_{24} = -0.84 \pm 0.28$) for their (uncorrected) data.

With the exception of objects which are morphologically identified as radio-loud AGN, the overwhelming majority of optically obscured Spitzer sources with a radio counterpart either in the Condon et al. (2003) or in the Morganti et al. (2004) catalogues agree, although with a large scatter, with the Appleton et al. (2004) relation. Furthermore, a similar behaviour is also found for the upper radio limits of those sources which do not have a radio counterpart in either the Condon et al. (2003; upper set of arrows at $F_{1.4\,\text{GHz}} \simeq 0.1\,\text{mJy}$ in Figure 10) or Morganti et al. (2004; lower set of arrows at $F_{1.4\,\text{GHz}} \simeq 0.06\,\text{mJy}$ in Figure 10) datasets. This is rather surprising for two reasons. The first one is that the above relation is observed to hold for any type of galaxy, independent of their mid-IR classification, and therefore also for AGN. Although this result is not striking per se as also most Seyfert galaxies are shown to follow the IR-radio correlation (see e.g. Roy et al. 1998), this suggests that the 1.4 GHz luminosity of all the sources examined in this work is dominated by star formation activity, despite the presence of an AGN. In this respect, the large scatter of our data around the Appleton et al. (2004) relation can be at least partially interpreted as due to a – less important – contribution of AGN origin, in general not observed to correlate with optical and/or IR emission (e.g. Andreani et al. 2003).

The second reason is instead intimately linked to the form of the SED of star-forming objects probed by Spitzer at redshift $z \sim [1.6 - 2.7]$. Such a redshift interval in fact samples the SED region which is dominated by strong silicate absorption and PAH emission lines (see Figure 6), which make the observed 24µm luminosity of these sources extremely variable even if one moves in redshift by a very small amount. Such an extreme variability most likely constitutes the dominant cause for the observed spread around the Appleton et al. (2004) relation. We note that a very similar result on the relation between 1.4 GHz and 24µm fluxes was obtained by Weedman et al. (2006), even though for a much smaller sample of $z \sim 2$, mid-IR bright objects (both candidate AGN and starbursts) in the FLS.

When compared with what was found at 1.4 GHz, the sources in our sample seem to show a more loose trend between radio emission at 610 MHz and mid-IR fluxes. The right-hand panel of Figure 10 visualizes this result and also indicates that, if anything, some kind of a correlation similar to that found by Appleton et al. (2004) could only be envisaged if our population of radio-identified Spitzer sources present an average radio spectral index $\langle \alpha \rangle > 1$ (the value $\langle \alpha \rangle = 2$ chosen for the dotted line in Figure 10 is simply to guide the reader’s eye), in agreement with what found in §5.1 from an investigation of the radio number counts for these sources. We will investigate this issue in greater detail in the next Section.

6 THE RADIO SPECTRAL INDEX

While the analysis performed in §5.1 and §5.2 could only provide information on the average radio spectral properties of the population of radio-identified Spitzer sources set at $z \sim 2$, a direct estimate of the 610 MHz-to-1.4 GHz radio spectral index $\alpha$ is possible for all those sources which present detected radio fluxes at both the investigated frequencies.
Figure 14. $24\mu m$ vs 1.4 GHz (left-hand side) and 610 MHz (right-hand side) fluxes for objects with different radio spectral index $\alpha$. Crosses in the left-hand panel identify those sources which do not have a 610 MHz counterpart, while those on the right-hand panel are for objects without 1.4 GHz fluxes above the detection thresholds (see text for details). The line coding is as in Figure 10.

Figure 12. Radio spectral index $\alpha$ as a function of $F_{24\mu m}$ flux density. Filled (red) dots are for AGN, (green) squares for star-forming galaxies, while (blue) triangles are for unclassified objects. Upper and lower limits are also indicated as colour-coded. Crosses indicate those sources whose radio activity is most likely associated to a radio-loud AGN (see text for details). The dashed line marks the transition between flat-spectrum and steep-spectrum radio objects ($\alpha \sim 0.5$).

Figure 13. Fractional distribution of radio spectral indices $\alpha$. The dotted (blue) line corresponds to all faint radio sources identified at both 610 MHz and 1.4 GHz (1516 objects), the dashed (red) line is for the subsample of $z \sim 2$ Spitzer-selected sources (43 objects), while the solid (green) line represents the result obtained by also including in the $z \sim 2$ Spitzer sample objects with estimated upper and lower limits on $\alpha$ (56 objects).

Under the assumption of a power-law behaviour for the SED in the radio interval between 610 MHz and 1.4 GHz, $\alpha$ was then calculated for 45 objects belonging to our sample. 12 lower limits and 3 upper limits have been furtherly added to our list of estimated $\alpha$’s as explained here. Since the Condon et al. (2003) survey is deeper than the FLS GMRT of Garn et al. (2007) ($\sim 100\mu Jy$ vs $\sim 200\mu Jy$; see §2.2), we expect all the sources detected in the Garn et al. (2007) dataset to be also detected in the Condon et al. (2003) 5$\sigma$ maps unless they have steep, $\alpha \geq 0.5$ radio spectra. 12 optically faint Spitzer sources have a radio counterpart in the GMRT only,
and the lower limits for their radio spectral indices have been estimated as \( \alpha_{\text{low}} = \log_{10}(100\, \mu\text{Jy}/F_{610\,\text{MHz}}[\mu\text{Jy}])/(\sim -0.36) \), where \(-\) as shown above \(- 100\, \mu\text{Jy} \) approximately corresponds to the completeness limit probed by the Condon et al. (2003) survey. Conversely, there are three sources which are relatively bright at 1.4 GHz, and for which one would have also expected a detection at 610 MHz unless endowed with inverted (i.e. negative values of \( \alpha \)) spectra. For these sources with \( F_{1.4\,\text{GHz}} \gtrsim 400\, \mu\text{Jy} \) (corresponding to the limit for completeness of the GMRT survey in the case of \( \alpha = 0 \)), the lower limits in their radio spectral indices were instead estimated as \( \alpha_{\text{low}} = \log_{10}(F_{1.4\,\text{GHz}}[\mu\text{Jy}]/400[\mu\text{Jy}])/(\sim -0.36) \). All the remaining sources have 1.4 GHz fluxes which are faint enough to account for non-detection at 610 MHz. No estimate of \( \alpha \) was possible for these objects.

Values for the radio spectral index for the sources in our sample estimated as above are given in Table 1. Figures [11] and [12] show their trend as a function respectively of 1.4 GHz, 610 MHz and 24 \( \mu \)m fluxes for the three sub-classes of AGN (red circles), star-forming galaxies (green squares) and unclassified objects (blue triangles). As it was in §5.2, sources with radio morphologies which suggest the presence of a radio-loud AGN have been excluded from our analysis and have been marked with a cross in the various plots.

Two main features can be gathered from the investigation of Figures [11] and [12]. The first one is that there is no relationship between the distribution of \( \alpha \) values and either radio/mid-IR fluxes. The second, intriguing finding is that there are very few flat-spectrum sources with \( \alpha < 0.5 \), in agreement with the results of §5.1 and §5.2. The overwhelming majority of our objects (36 if one also includes the lower limits, value which becomes 34 by removing the low-z interlopers) instead presents very steep, \( \alpha > 1 \) spectral indices, some of them even reaching values of \( \alpha \sim 2.5 \).

Giving the limiting fluxes of the Condon et al. (2003) and Garn et al. (2007) surveys, the distribution of radio spectral indices as obtained by matching these two datasets will necessarily be biased towards high, \( \alpha \gtrsim 0.5 \), figures. Therefore, in order to assess the statistical significance of our findings, we have compared the distribution of \( \alpha \) values for all the sources which appear in both the GMRT and Condon et al. (2003) catalogues (1516 objects to a separation between 610 MHz and 1.4 GHz positions \( d = 6'' \)) with the distribution obtained for our sample of \( z \sim 2 \) radio-detected Spitzer galaxies. As Figure 13 shows, although in general not too different from that of the totality of radio sources (a KS test reports values of 0.99 and 0.98 respectively if one considers radio detections only or also takes into account upper and lower limits on \( \alpha \)), the distribution of \( \alpha \) in the case of Spitzer galaxies (dashed – red – line) is systematically shifted towards higher values of the radio spectral index. This trend becomes even stronger if one also includes in the analysis the upper and lower limits on \( \alpha \) (solid – green – histogram in Figure 13), estimated as discussed above. The statistical significance of this high-\( \alpha \) tail is quite high: for the whole population of faint radio sources with identifications at both 610 MHz and 1.4 GHz we have that the percentage of sources with \( \alpha \gtrsim 1 \) is 43%, while this number rises to 60% (i.e. 26 galaxies out of 43 or 34 out of 56 by also including upper and lower limits on \( \alpha \), see Table 1) for the sample of \( z \sim 2 \) Spitzer galaxies.

This result is quite surprising. Very steep radio spectral indices tend to identify the population of Ultra Steep Spectrum sources (USS), mostly radio-loud galaxies set at substantial redshifts. Indeed, objects with high values of \( \alpha \) are typically investigated to look for very high redshift radio galaxies (e.g. De Breuck et al. 2000; 2002). However, the objects in our sample are not ‘a priori’ radio-loud AGN as they have been merely selected as high-z, strong mid-IR emitters. Furthermore, we find that the majority of our sources present values of \( \alpha > 1 \) independent of whether their mid-IR emission is indicative of a starburst-dominated galaxy or of obscured AGN activity.

Taking at face value our results, one would then conclude that the overwhelming majority of the sources in our radio-identified sample is made of radio-loud AGN. This is however in striking disagreement with the findings of §5.2 which show that most of the very same objects follow a 24\( \mu \)m-to-1.4 GHz relation between fluxes which closely resembles that typical of starburst-powered galaxies. Indeed, if one reproduces the \( F_{24\mu\text{m}}/F_{1.4\,\text{GHz}} \) plot, this time by grouping together sources with similar values of \( \alpha \) (where the three broad classes are \( \alpha < 0.4 \), flat-spectrum AGN; \( 0.4 \leq \alpha \leq 1 \), possible starbursts; \( \alpha > 1 \) USS; see Figure 14), it is clear that, while all but one of the objects with \( 0.4 \leq \alpha \leq 1 \) do fall in the allowed region identified by the Appleton et al. (2004) relation, the same can be said for the majority of sources with \( \alpha > 1 \). It is however comforting that most flat-spectrum sources in our sample – in many cases coinciding with those objects which present a radio morphology typical of a radio-loud AGN – do instead lie outside the ’allowed’ range for radio emission from star formation activity.

A natural explanation which can reconcile the above discrepant findings is provided by envisaging a two-component radio spectrum, where the flatter \( \alpha_{\text{sp}} \sim 0.8 \) component originates from processes associated to star-formation, while the steeper \( \alpha_{\text{AGN}} \sim 2 \) one is due to the presence of an AGN. In such a two-component model, the 1.4 GHz emission would primarily stem from star formation, while the 610 MHz signal could mainly be attributed to the radio-loud AGN. This framework could then also explain why the 1.4 GHz emission in these sources follows that of star forming systems, while the relation is more loose in the case of 610 MHz and 24\( \mu \)m fluxes (see Figure 13). We note that, an implicit but very important implication of the above discussion is of a cohabitation of the two processes of star formation and accretion onto an AGN, both expected to take place at the same time within the same systems.

A number of works can be found in the literature which try to explain the presence of systems with very steep spectral slopes at high redshifts. For instance, by comparing the extremely steep spectral index sources associated with galaxies residing closest to the cluster centres, Klammer et al. (2006) found that steeper spectra can be explained by pressure-confined radio lobes which have slow adiabatic expansion losses in high-density environments. Alternatively, one can attribute the steepening of the radio spectrum at low frequencies as due to the scattering between CMB photons and relativistic electrons at \( z \sim 2 \) where the CMB energy density is significantly higher than it is at later epochs (e.g. Martinez-Sansigre et al. 2006). Both theories need high-z radio sources to reside in very dense environments. This is in agreement with the results of Magliocchetti et al. (2007; 2007a) which find the parent population
of these radio-identified Spitzer sources to be hosted by very massive/cluster-like structures. Furthermore, recent clustering studies performed on the class of USS also find the latter objects to reside in $M > 10^{11.4} M_\odot$ systems (Bornancini et al. 2006). The remarkable similarity between the Magliocchetti et al. (2007; 2007a) and Bornancini et al. (2006) results indicate that USS and $z \sim 2$ Spitzer-selected sources reside in very similar environments, finding which strengthens the case for a relationship between these two populations.

7 CONCLUSIONS

This paper has presented an analysis of the radio properties of a subsample of optically faint ($R > 25.5$), 24µm-selected galaxies observed by Spitzer in the FLS (Magliocchetti et al. 2007). These objects have been cross-correlated with a number of radio catalogues which cover the same region of the sky, namely that of Condon et al. (2003) which probes 1.4 GHz fluxes brighter than $\sim 100 \mu$Jy, of that of Garn et al. (2007) – which probes 610 MHz fluxes brighter than $\sim 200 \mu$Jy – and, on a smaller portion of the sky, that of Morganti et al. (2004) which reaches 1.4 GHz fluxes as faint as $\sim 40 \mu$Jy.

70 optically faint Spitzer sources have been identified in the Condon et al. (2003) catalogue, 33 in the Morganti et al. (2004) dataset, while 52 are found in the survey performed by Garn et al. (2007). After performing a number of corrections to account for multiple identifications, sources erroneously split in the original Spitzer catalogue into different components and mid-IR objects with real radio counterparts at one of the two radio frequencies which were further away than the allowed (10") matching radius, we end up with a sample of 96 radio-identified, optically faint, mid-IR emitting sources, 45 of which have an identification at both 1.4 GHz and 610 MHz. The fraction of radio identifications is a strong function of 24µm flux: almost all sources brighter than $F_{24 \mu m} \sim 2$ mJy are endowed with a radio flux at both 1.4 GHz and 610 MHz, while this fraction drastically decreases by lowering the flux level.

IRAC photometry for all those sources which also have detected fluxes in at least one of the four 8µm, 5.8µm, 4.5µm and 3.6µm channels (64 out of 96), allows to classify them into two categories: obscured AGN (45 sources) and systems mainly powered by starformation activity, (SB, 13 objects). We also find five low-z (i.e. $z \lesssim 0.5$ m51-type) interlopers, while the remaining 33 sources are unclassified. Furthermore, with the help of IRAC photometry it was possible to assign broad redshift intervals to all those sources (mostly AGN) which presented in the lowest 3.6µm and 4.5µm wavelength channels of IRAC a ’bump’ compatible with being produced by an evolved (old) stellar population. The majority ($\sim 66\%$) of these galaxies reside at redshifts $z \gtrsim 1$, in agreement with other studies mainly based on mid-IR and near-IR spectroscopy of optically faint, 24µm-selected galaxies (i.e. Weedman et al. 2006; Yan et al. 2005; 2007; Brand et al. 2007). We stress that this inferred fraction can only be considered as a lower limit to the real portion of faint Spitzer sources set at high redshifts. In fact, because of their characteristic spectral properties in the mid-IR regime, we expect the majority of star forming systems (too faint at the IRAC frequencies to have measurable 3.6µm and/or 4.5µm fluxes) to be indeed located in the $z \sim [1.6 – 2.7]$ redshift range.

A small fraction of objects in our sample present radio morphologies such as jets and/or lobes compatible with them being identified as radio-loud AGNs. Interestingly enough, we find that for most of these few extended radio sources the mid-IR emission is associated to such peripheral regions rather than stemming from the centre of radio activity, generally coinciding with the location of the AGN. However, the majority of the objects in our sample present unresolved radio images.

A compared analysis of the radio number counts for optically obscured Spitzer sources indicates that the $\Delta N / \Delta F$ as estimated at 1.4 GHz can only be reconciled with what found at 610 MHz if the population under investigation is endowed with an average value for the radio spectral index (defined as $F_R \propto \nu^{-\alpha}_R$, where $F_R$ is the radio flux and $\nu_R$ the generic radio frequency) ($\alpha$) $\gtrsim 1$. Classical, 'flat spectrum' radio sources can confidently be excluded as the typical objects constituting our sample. Furthermore, we have found that the radio number counts of sources classified as AGN and of those identified as starburst galaxies are quite similar, evidence which suggests that radio emission in $z \sim 2$ Spitzer galaxies originates from similar process(es), despite of the different mid-IR emission.

Direct investigations of the relation between 24µm and 1.4 GHz fluxes show that the overwhelming majority of those galaxies not excluded from our analysis because morphologically classified as radio-loud AGN follow the relationship identified for $0 \lesssim z \lesssim 1$ star-forming objects by Appleton et al. (2004), although with a large scatter. This happens regardless of whether the galaxy has been classified as an AGN or a starforming system on the basis of its mid-IR colours. The distribution of 24µm vs 610 MHz fluxes is instead found to be more scattered.

The majority of these radio-identified objects (26, a figure which rises to 34 if one also includes sources with estimated lower limits on $\alpha$) present very steep, $\alpha > 1$ radio spectral indices, some galaxies being endowed with $\alpha$’s as high as 2.5. This excess of galaxies with large $\alpha$ values is statistically significant as it corresponds to 60 per cent of our sample, to be compared with the 43 per cent found by considering the whole population of faint radio objects with an identification at both 610 MHz and 1.4 GHz.

Such very high figures for $\alpha$ would identify the corresponding sources as Ultra Steep Spectrum galaxies, generally high redshift radio-loud AGN. However this is in striking disagreement with what found for the relation between 24µm and 1.4 GHz fluxes for the very same objects, relation which would explain their (1.4 GHz) radio emission as mainly due to processes connected with star forming activity.

A natural explanation to the above issues could be found by assuming that AGN and star-formation activity are concomitant in the majority of $z \sim 2$, Spitzer sources, at least in those which present enhanced radio emission. The radio signal stemming from these systems would then simply be the combination of two components: a shallower one – dominating the spectrum at 1.4 GHz – due to processes connected with star formation, and a steeper one – being responsible for most of the 610 MHz signal – connected with AGN activity. This framework could then also explain why
the 1.4 GHz emission in our sources follows that of star forming systems, while the same does not seem to happen in the case of 610 MHz fluxes.

Various explanations can be found in the literature to account for the presence of USS: from slow adiabatic expansion losses in high-density environments (e.g. Klamer et al. 2006) to the scattering between CMB photons and relativistic electrons at $\sim 2$ (e.g. Martinez-Sansigre et al. 2006). However, the results presented in this work might provide an alternative scenario. In fact, they suggest that high values for $\alpha$ might be due to the concomitant presence within the same systems of an AGN and of a star forming region: the AGN expansion would then be halted by the encounter with the cooler/denser sites in which star formation takes place. This would determine the ‘strangling’ of the AGN, causing its radio spectrum at low radio frequencies to steepen. Clearly, more theoretical work is needed in order to quantify the above issue and we are planning to present it in a forthcoming paper. For the time being, we note that intense star forming activity within a high redshift galaxy host of a USS has been recently reported by Hatch et al. (2007).

From a more observational point of view, the ‘ultimate truth’ on these sources could only come from very high resolution (and, given their faintness, sensitivity) measurements, capable to clearly disentangle the emission related to the AGN to that associated to star forming regions. The advent of instruments such as ALMA will then provide the answers we need.

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8 APPENDIX

This Section provides some more detailed information and images for the most interesting sources found in our work. Comments on the likeliness of multi-component associations are mainly based on the method introduced by Magliocchetti et al. (1998).

- J171239.2+591350. Possibly a triple radio source whereby the 24µm signal stems from the centre of radio emission (see middle panel in the last column of Figure [10]).
- J172258.9+59312 and J172259.9+593129. Extended radio source made by two distinct components (see middle panel in the second column of Figure [10]) both at 24µm and at 1.4 GHz. The 610 MHz emission is instead only observed
Figure 15. Radio maps for all but one of the sources of our sample brighter than $F_1 = 0.8$ mJy. The centre of each postage stamp (highlighted by a cross) corresponds to the position of 24µm emission. More detailed information on these objects is provided in the Appendix. Except for the two postage stamps at the top-centre and top-left panels which already appear in the Condon et al. (2003) paper, the radio data are un-published and come from the Condon et al. (2003) online FLS catalogue (available at http://www.cv.nrao.edu/sirtf/).

- J172256.4+590053. Possible triple radio source whereby the 24µm emission originates from one of the lobes (see upper panel in the last column of Figure 15).
- J171312.0+600840. Possible triple radio source whereby the 24µm emission originates from one of the lobes (see upper panel in the first column of Figure 15).
- J172018.1+592902. Single 24µm source split in the Spitzer catalogue into two components (J172018.1+592902 at the centre of the major component. Possibly a member of a double system.
- J171312.0+600840. Possible triple radio source whereby the 24µm emission originates from one of the lobes (see upper panel in the first column of Figure 15).
Figure 16. Radio maps for all those radio sources fainter than $F_{1.4\text{GHz}} = 0.8$ mJy which present possible extended/multi-component radio emission. The centre of each postage stamp (highlighted by a cross) corresponds to the position of 24\,$\mu$m emission. More detailed information on these objects is provided in the Appendix. Radio data from the Condon et al. (2003) online FLS catalogue (available at http://www.cv.nrao.edu/sirtf/).

- J171527.1+585802. Possible double radio source, with the 24\,$\mu$m emission originating from one of the lobes (see middle panel in the first column of Figure 16). Bright object both in the radio and mid-IR bands.
- J172305.1+593841. Possible double radio source, with the 24\,$\mu$m emission originating from one of the lobes (see upper panel in the second column of Figure 16).

and J172018.1+592859). The 24\,$\mu$m flux reported in Table 1 is the sum of those of the two sub-components.

- J171527.1+585802. Possible double radio source, with the 24\,$\mu$m emission originating from one of the lobes (see middle panel in the first column of Figure 16). Bright object both in the radio and mid-IR bands.
- J172305.1+593841. Possible double radio source, with the 24\,$\mu$m emission originating from one of the lobes (see upper panel in the second column of Figure 16).
• J171948.6+585133. Extended radio source (see middle panel in the first column of Figure 16).
• J171538.3+593540. Possible (but not likely) triple radio source with 24\(\mu\)m radio emission originating from one of the lobes (see bottom panel in the first column of Figure 16).
• J172056.6+590206. Possible (but not likely) triple radio source with 24\(\mu\)m emission coinciding with the centre for radio emission (see bottom panel in the last column of Figure 16).
• J172018.5+601237. Possible (but not likely) triple radio source with 24\(\mu\)m radio emission originating from one of the lobes (see bottom panel in the second column of Figure 16).
• J171628.4+601342. Single 24\(\mu\)m source split in the Spitzer catalogue into three components (J171628.4+601342, J171628.4+601334, J171627.2+601342). The 24\(\mu\)m flux reported in Table 1 is the sum of those of the three sub-components.
• J172353.2+601354. Single 24\(\mu\)m source split in the Spitzer catalogue into two components (J172353.2+601354 and J172353.2+601351). The 24\(\mu\)m flux reported in Table 1 is the sum of those of the two sub-components.
• J171054.4+594426. Bright radio source. The 24\(\mu\)m emission originates from a lateral radio blob, possibly a jet (see upper panel in the first column of Figure 15).
• J171433.9+600741. Very bright triple source, which appears in the Condon (2003) catalogue as split into 7 components. The 24\(\mu\)m emission originates from one of the lobes (see upper panel in the second column of Figure 15). Surprisingly enough, it does not have a 610 MHz counterpart within 30 arcsec from the centre of 24\(\mu\)m emission.
• J172005.0+592430. Very bright and extended triple component, which appear in the Condon (2003) catalogue as split into 5 components. The 24\(\mu\)m emission originates from the centre of one of the lobes (see the upper panel in the last column of Figure 15).
• J172103.6+585052. Close double system, whereby the 24\(\mu\)m originates from the smaller/fainter of the two radio components (see middle panel in the second column of Figure 15).
• J171427.8+592828. Radio flux from the Morganti et al. (2004) catalogue. 24\(\mu\)m emission associated to a lateral/jet-like blob. Possibly member of a double system (see bottom panel in the second column of Figure 15).
• J171207.6+593956. Composite radio system formed by a bright central source which coincides with the centre of 24\(\mu\)m emission and a much fainter/smaller lateral blob, possibly a jet (see bottom panel in the first column of Figure 15).
• J172048.0+594320. Composite radio system formed by a bright central source which coincides with the centre of 24\(\mu\)m emission and a much fainter/smaller lateral blob, possibly a jet (see middle panel in the last column of Figure 15).
• J171417.6+600531. 24\(\mu\)m emission from lateral and faint blob (see bottom panel in the last column of Figure 15). No 610 MHz emission despite the relatively high 1.4 GHz flux.
• J172217.4+601003. 24\(\mu\)m emission far from radio image of closest 1.4 GHz source. Likely a mis-identification.