The Radio–Mid-Infrared Correlation and the Contribution of 15-$\mu$m Galaxies to the 1.4-GHz Source Counts

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ABSTRACT
The radio counterparts to the 15-$\mu$m sources in the European Large Area ISO Survey southern fields are identified in 1.4-GHz maps down to $\sim 80$ mJy. The radio - MIR correlation is investigated and derived for the first time at these flux densities for a sample of this size. Our results show that radio and MIR luminosities correlate almost as well as radio and FIR, at least up to $z \sim 0.6$. Using the derived relation and its spread together with the observed 15-$\mu$m counts, we have estimated the expected contribution of the 15-$\mu$m extragalactic populations to the radio source counts and the role of MIR starburst galaxies in the well known 1.4-GHz source excess observed at sub-mJy levels. Our analysis demonstrates that IR emitting starburst galaxies do not contribute significantly to the 1.4-GHz counts for strong sources, but start to become a significant fraction of the radio source population at flux densities $\lesssim 0.5$ – 0.8 mJy. They are expected to be responsible for more than 60% of the observed radio counts at $\lesssim 0.05$ mJy. These results are in agreement with the existing results on optical identifications of faint radio sources.

Key words: galaxies: evolution – galaxies: starburst – cosmology: observations – infrared: galaxies – radio continuum: galaxies.

1 INTRODUCTION

With a thousand times better sensitivity than the IRAS 12-$\mu$m data, the LW3 observations (in the 12 – 18 $\mu$m waveband, centred at $\lambda = 15 \mu$m) with the ISOCAM camera (Cesarsky et al. 1996) on the Infrared Space Observatory (ISO, Kessler et al. 1996) have allowed us for the first time to perform sensitive surveys of distant infrared galaxies (up to $z \sim 1.5$) in the Mid-Infrared (MIR) band. The extragalactic source counts derived from these 15-$\mu$m surveys, including large area shallow surveys like ELAIS (Oliver et al. 2000) covering the flux density range $0.5 \lesssim S_{15 \mu m} \lesssim 150$ mJy (Lari et al. 2001), and small area deep integrations reaching $S_{15 \mu m} \sim 0.05$ – 0.1 mJy (Elbaz et al. 1999), show a strong departure from no evolution predictions at low flux densities ($\lesssim 1$ – 2 mJy; Elbaz et al. 1999; Gruppioni et al. 2002). According to both optical identification works (Aussel et al. 1999; Elbaz et al. 1999; Pozzi et al. 2003) and theoretical models (i.e. Franceschini et al. 2001), the sources responsible for the sharp upturn observed in the number counts at faint flux densities are mainly star-forming galaxies at moderately high redshifts ($0.4 \lesssim z \lesssim 1.4$).

A tight correlation between Far-Infrared (FIR) and radio continuum for star-forming galaxies is locally well assessed over a large range of luminosities, from normal spirals to the more extreme Ultraluminous Infrared Galaxies (ULIGS; $L > 10^{12}L_\odot$), as shown by several authors (Condon 1992; Cram et al. 1998; Yun, Reddy & Condon 2001). So far there have been many attempts to explain the tightness of this correlation, whose origin is still somewhat unclear. It is generally assumed that massive stars are responsible for both the UV photons heating the dust, which re-radiates in the infrared band, and the acceleration of relativistic electrons, producing the radio continuum, after their explosion as supernovae. Such a tight local correlation does not necessarily hold in the distant Universe and, even in this case, it would be interesting to investigate possible variations with redshift of the slope and/or normalization of the correlation. Moreover, it is not obvious that the radio continuum should correlate with the MIR emission (produced by a mixture of stochastic heating from Polycyclic Aromatic Hydrocarbons (PAH; i.e. Puget & Leger 1989) and thermal emission at high temperature) as well as with the FIR (resulting from thermal emission of large dust grains at lower temperature).

The aim of this paper is to study for the first time the radio-
In order to investigate the radio–MIR correlation within our ISO-CAM sample, we have first cross-correlated the 15 μm and the 1.4-GHz catalogues (complete at the 5σ level) in S1 and S2, finding 28 and 13 coincidences respectively within a distance of 5 arcsec. Note that the S1 15-μm catalogue considered for this analysis is the same, conservative, catalogue used to derive the source counts (see Gruppioni et al. 2002), where 35 possibly spurious sources (all with \( S < 1.5 \) mJy) have been excluded after a visual inspection of their pixel history. These sources, detected above the 5σ threshold on the maps obtained through a combination of several images, are too faint to be distinguished from noise on the single pixel histories without uncertainty (see Gruppioni et al. 2002 for further explanation). Then, at each ISO-CAM position, we have searched for detection in the radio maps down to 3σ, finding 53 additional radio identifications within 5 arcsec (46 in S1 and 7 in S2), for a total of 94 ISO–radio associations with \( S_{1.4 \ GHz} \geq 3\sigma\). The number of expected spurious coincidences, on the basis of the density of ISO and radio sources and of the adopted maximum distance (5 arcsec) is of the order of one. Seventy-three of these sources have spectroscopic data and redshift measurements in the spectroscopic data sample available by October 2002 (additional spectra taken in the October run were not used in this work).

Table 1 lists the percentage of radio detections as a function of the 15-μm flux density. The first two columns give the flux density range and the corresponding average flux density respectively, whilst the following columns give the total number of ISO-CAM extragalactic objects, the number of radio detections, the number of non-AGN radio detections(in brackets) and the corresponding fraction (i.e. radio detections over total number of extragalactic sources in that bin). At high flux densities all the 15-μm extragalactic sources have a radio counterpart, while the fraction of radio identifications decreases at lower 15-μm flux densities. This is due to the fact that our radio maps are not deep enough to allow the detection of all our 15-μm luminous sources. In particular, the fainter ones. Figure 1 (left panel) shows the 1.4-GHz luminosity versus the 15-μm luminosity for the 65 ISO-CAM galaxies with spectroscopic identification detected in the radio band (open circles). As radio K-correction we have applied a power law with a slope \( \alpha=0.7 \), whilst at 15 μm we have applied the K-corrections derived by Franceschini et al. (2001) using different template Spectral Energy Distributions (SEDs) for the different populations (M82 for starbursts and type 2 AGN, M51 for normal spirals) modelling the 15-μm source counts.
we have recomputed the radio–MIR luminosity correlation for the entire sample of 331 MIR-selected galaxies by using ASURV (the Survival Analysis Package which uses the routines described in Isobe, Feigelson & Nelson 1986 and takes into account also the upper or lower limits in a sample). A redshift has been assigned to the 192 sources without spectroscopic information by using the empirical correlation (and its spread) between the 15-µm flux densities and redshifts found for our 139 spectroscopically identified galaxies:

\[
\log(z) = -(0.68 \pm 0.04) - (0.37 \pm 0.06) \log(S_{15 \, \mu m}[mJy]) + G(0, \sigma_{rel})(2)
\]

where \(\sigma_{rel} (= 0.25)\) is the 1σ dispersion of the relation and \(G(0, \sigma_{rel})\) is a Gaussian distribution with centre 0 and width \(\sigma_{rel}\). For the extragalactic sources not detected in the radio we have adopted an upper limit to the 1.4-GHz flux density equal to their corresponding 3σ value on radio maps. Under these assumptions, we have re-determined the radio-MIR correlation through ASURV, obtaining:

\[
\log\left(\frac{L_{1.4 \, GHz}}{L_{\odot}}\right) = (1.08 \pm 0.04) \log\left(\frac{L_{15 \, \mu m}}{L_{\odot}}\right) - (6.07 \pm 0.41)
\]

with a dispersion of \(\sim 0.34\) dex. This relation, shown as dot-dashed line in the left panel of figure 1, is somewhat more scattered than and lies about a factor of 2 below the previous determination. The right panel of figure 1 shows the radio to MIR luminosity ratio versus MIR luminosity. Our estimate of the “real” correlation (dot-dashed line) has a lower normalization than the local radio–FIR correlation (dotted line; extrapolated to radio–MIR as described below), which is instead much closer to our determination for detections only (dashed line). The local relation corresponds to a local value of the “\(q\)” parameter equal to 2.34 (defined as \(q \equiv \log(L_{FIR}|W|)/(3.75 \times 10^{12}|Hz|) \times 1/L_{1.4 \, GHz}[WHz^{-1}]\)), where the FIR flux is defined to be \(1.26 \times 10^{-16}(2.58S_{15\mu m} + S_{100\mu m})\) [W m\(^{-2}\); see Condon et al. 1991] and is converted to MIR through the empirical relations between \(L_{FIR}\) and \(L_{15 \, \mu m}\) found locally by Elbaz et al. (2002). In the same figure we also show the relation derived (using the same K-corrections and cosmological parameters considered in our analysis) from the radio and 15-µm data for 19 ISOCAM sources detected in the WSRT deep radio survey of the HDF-N region (see Table 1 in Garrett 2002). This radio–FIR correlation (shown as dot-dot-dot-dashed line in the figure) has a normalization significantly higher (about a factor of 5) than our best-fitting relation and is also higher than the local one. Note, however, that this relation is derived using only the radio detections with spectroscopic \(z\), without taking into account the radio upper limits. Since the number of upper limits is similar to that of the detections (which constitute \(\sim 40\)% of the 15-µm sample detected at \(>5\sigma\) level), it is likely that, as we find for our data, the “real” correlation would have a somewhat lower normalization. Despite this, the comparison of our data with those in the HDF-N region suggests a possible change in normalization of the radio–MIR correlation at the higher redshifts sampled by the HDF-N ISO selected galaxies. Alternatively, the two sets of data (ELAIS and HDF-N surveys) could be made consistent with each other if the ISO or the radio data in the two fields were on a different flux scale (i.e. underestimated ISO or overestimated radio flux densities in the HDF-N).

Despite the difference in normalization between our radio–infrared correlation and the local one, which seems to suggest a change in the radio–infrared correlation with redshift, the impor-
The principal results of our analysis are that radio and MIR luminosities for galaxies strongly correlate with each other, almost as well as that found for the radio and FIR, and at significantly higher redshifts than those explored by IRAS. This implies a possible correlation between the PAH emission and the radio (and FIR) luminosity. The somewhat larger dispersion with respect to that observed for the radio–FIR relation is due to the large spread in the mixture of PAH and thermal emission at the high temperatures responsible for the radiation observed in the MIR band, or to the complicated shape of the galaxy SEDs in that wave-band, which introduces uncertainties and significant object-to-object variations in the MIR K-correction.

Figure 2 shows the ratio between 1.4-GHz and 15-μm flux densities as a function of redshift for our spectroscopically identified galaxies. Diagonal crosses are the median values of the ratio in different redshift intervals (z < 0.1, 0.1 ≤ z < 0.2, 0.2 ≤ z < 0.3 and z ≥ 0.3), plotted in correspondence of the median redshift. The dashed line shows the expected change with z of S_{1.4GHz}/S_{15 μm} due to the difference between the average radio and MIR starburst K-corrections (normalised to the median value for our data, corresponding to S_{1.4GHz}/S_{15 μm} = 0.15) at z = 0.

The somewhat larger dispersion with respect to that observed for the wave-band (note however above that our radio detections describe the upper envelope – i.e. stronger radio sources – of the radio–MIR correlation, rather than the entire population). Despite the relatively large spread in the values of the radio–MIR flux density ratio, no obvious trend with redshift is seen in our data for z ≥ 0.07. All the objects below this redshift show values of their radio to MIR flux density ratios which are significantly lower than the mean. One possible reason for this might be that we have missed some extended emission in some of these sources. In fact, about half of the very low redshift sources have a weak radio emission (detected below the 5σ threshold) therefore, because of the low signal-to-noise ratio, their flux density may have been underestimated if their radio emission is more extended than the beam (∼ 15″). Indeed, most of these faint radio sources at low redshift are bright and extended in both optical and MIR (∼ 40″ – 1″).

4 CONTRIBUTION OF MIR GALAXIES TO THE RADIO SOURCE COUNTS

In order to estimate the contribution made to the radio source counts from infrared galaxies, we have convolved the correlation between radio and 15-μm luminosities derived in the previous section with the evolutionary model for spiral and starburst galaxies which fits the 15-μm source counts in S1 (Gruppioni et al. 2002).

The intrinsic dispersion adopted for the radio–MIR correlation (σ ∼ 0.28 dex) has been derived by subtracting from the observed value (∼ 0.34 dex) the estimated contributions from the uncertainties on the radio and 15-μm observed flux densities (∼ 0.08 and 0.10 dex, respectively) and the radio and 15-μm K-corrections (∼ 0.02 and 0.15 dex, respectively). The resulting predicted source counts for starburst + Seyfert 2, normal spiral and all galaxies, are plotted in figure 3 as dashed, dotted and solid lines respectively. As a consistency check, we have derived the radio counts of our ISO selected galaxies directly from the data. Each radio detected ISO galaxy has been weighted by its radio and MIR spatial coverage and the contribution from all the radio detections in radio bins have been summed to produce the counts shown as filled circles in figure 3. The data points are in excellent agreement with the model predictions; in particular, the star-forming population would be responsible for about 40% – 60% of the observed counts at S_{1.4GHz} ∼ 50 – 100 μJy. Therefore, starburst galaxies would make up most of the observed radio counts at μJy level, in agreement with the results from very deep radio surveys, like that in the HDF-N, where ∼ 80% of sources detected at S_{1.4GHz} > 16 μJy have been identified with starburst galaxies (Richards (2000)). Conversely, the fractional contribution of starburst galaxies to the radio counts decreases rapidly above S_{1.4GHz} ∼ 0.1 mJy; in good agreement with spectroscopic identifications at the sub-mJy level, which find ∼ 60–70% of elliptical galaxies and AGN1 among the optical counterparts of S_{1.4GHz} ≥ 0.2 mJy radio sources (Gruppioni, Mignoli & Zamorani 1999).

Given the differences in the normalization of the relations between radio and MIR luminosities derived from different samples (see previous section), we have computed the expected radio counts by increasing the normalization of our best-fitting correlation by a factor of 2, in such a way to bring it on the same scale as the local correlation. The resulting (total) counts are shown by the thin solid line in figure 3. The higher normalization relation produces a contribution to the radio counts which is far too high with respect to the observed data and exceeds the total radio counts at S_{1.4GHz} ≥ 0.3 mJy. Of course, this result is produced by the combination of the radio–MIR correlation and a model fitting the source counts. However, the model considered here is the only one able to fit the 15-μm counts in S1, which are lower than the other existing ones. Therefore, a radio–MIR correlation with a normalization significantly higher than that found in this work seems to be inconsistent with the observed faint 1.4-GHz source counts.

5 CONCLUSIONS

By searching for 3σ detections on deep ATCA 1.4-GHz maps of the southern ELAIS fields S1 and S2, and cross-correlating these with 15-μm extragalactic objects detected respectively by Lari et al. (2001) and by Pozzi et al. (2002, in preparation), we have obtained a sample of 84 MIR-radio galaxies (65 of which have measured redshifts).

These data have allowed us for the first time to study with a statistically significant sample of objects, the radio–MIR correlation and the radio and infrared properties of galaxies to much larger distances and fainter flux densities than previously achieved with IRAS.

The principal results of our analysis are the following:
1. The radio–MIR correlation for MIR selected galaxies with a radio detection in our radio maps is well described by an approximately linear relation, with a scatter of $\sim 0.27$ dex (similar to that found for the local radio–FIR relation), implying that PAH band emission correlates with FIR and radio luminosity and that the locally determined correlation between radio and infrared emission for star-forming galaxies persists to cosmological distances ($z \sim 0.6$).

2. If we consider also the radio upper limits we can obtain an estimate of the “real” radio–MIR correlation, unbiased by the radio non-detections. We still obtain a strong correlation between radio and MIR luminosities, but with a factor 2 lower normalization and a larger spread ($\sim 0.34$ dex). The lower normalization of our relation corrected for upper limits with respect to the local radio–MIR relation (derived from the radio–FIR through a local FIR/MIR average ratio) implies a change in the radio–MIR correlation with increasing redshift.

3. There is no indication of any trend with $z$ in the radio–MIR correlation found for our data (apart the K-correction effects), up to $z \sim 0.6$.

4. The contribution of 15-$\mu$m galaxies to the radio source counts has been computed directly from our data and also by including the empirical radio–MIR correlation and its spread into the model fitting the MIR extragalactic source counts. Data and model agree very well and predict that MIR starburst galaxies should start contributing significantly ($\gtrsim 10\%$) to the radio counts around $0.5–0.8$ mJy, with their importance rapidly increasing until they make up $> 40 – 60\%$ of the observed counts at $S_{1.4} \lesssim 50 – 100$ mJy.

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Figure 3. Best-fitting model to our ELAIS 15-$\mu$m extragalactic source counts (in differential form, normalised to a Euclidean non-evolving distribution) converted to 1.4 GHz by considering the empirical relation found for our data and its spread. As explained in the plot, the thick solid line represents the expected total source counts, while the short-dashed and the dotted lines are respectively the modeled contributions of a population of strongly evolving starburst galaxies (plus Seyfert 2) and non-evolving spirals. The thin solid line is the total contribution from starburst and spiral galaxies obtained by increasing the radio–MIR relation normalization by a factor of 2. The filled circles are the counts of the S1 $15-$µ$m sources with $\geq 3\sigma$ 1.4-GHz counterpart. The dot-dashed line represents the fit of Windhorst, Mathis & Neuschaefer (1990) to the 1.4-GHz counts obtained from 24 different radio surveys. The filled squares are the total radio counts in the ELAIS regions (a combination of the S1 ATCA data of Gruppioni et al. 1999 with the VLA data in the northern ELAIS regions of Ciliegi et al. 1999). The open squares are the 1.4-GHz counts in the HDF-N from Richards (2000).

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