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Sub-arcsecond, microJy radio properties of *Spitzer* identified mid-infrared sources in the HDF-N/GOODS-N field

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Abstract.
We present recent and ongoing results from extremely deep 18 day MERLIN + VLA 1.4GHz observations (rms: 3.3microJy/bm) of an 8.5×8.5 arcminute field centred upon the Hubble Deep Field North. This area of sky has been the subject of some of the deepest observations ever made over a wide range of frequencies, from X-rays to the radio. The results presented here use our deep, sub-arcsecond radio imaging of this field to characterise the radio structures of the several hundred GOODS *Spitzer* MIR sources in this field. These MIR sources primarily trace the luminous starburst sources. A significant proportion of the MIR sources are detected and resolved by our radio observations, allowing these observations to trace the IR/Radio correlation for galaxies over ∼7 orders of magnitude, extending it to ever lower luminosities.

1. Introduction

Over the last 3 decades studies of the radio and far-infrared (FIR) properties of galaxies have shown there to be a tight correlation between the emission from galaxies in these two observing bands that extends over several orders of magnitude in luminosity (van der Kruit 1973; Condon *et al.* 1982). More recently investigations using the mid-infrared (MIR) bands at 24 μm and 70 μm of *Spitzer* by Appleton *et al.* (2004), have shown that the correlation of the MIR and FIR emission to the radio emission persist out to redshifts of at least 1, with deep field observations by Garrett (2002) tentatively extending this correlation out to $z \sim 4$. The correlation between the radio and infrared emission arises because both are related to the star formation processes; the infrared emission is produced from dust heated by photons from young stars, while the radio emission arises from synchrotron radiation produced by the acceleration of charged particles from supernovae explosions. Investigations of nearby star-forming galaxies (Murphy *et al.* 2006) have begun to extend this correlations to even fainter luminosities (down to $L_{24\,\mu m} \approx 10^{20}$ W Hz^{-1}) by considering discrete regions within individual galaxies. However, studies of deep field at radio and IR wavelengths still uniquely provide a method by which this correlation can be investigated using many faint galaxies out to high redshifts.

Deep radio observations of the HDF-N region were made in 1996-97 at 1.4 GHz using both MERLIN and the VLA. The initial results of these observation were presented in Muxlow *et al.* (2005), Richards *et al.* (1998) and Richards (2000). Within these radio observations 92 sources were detected brighter than

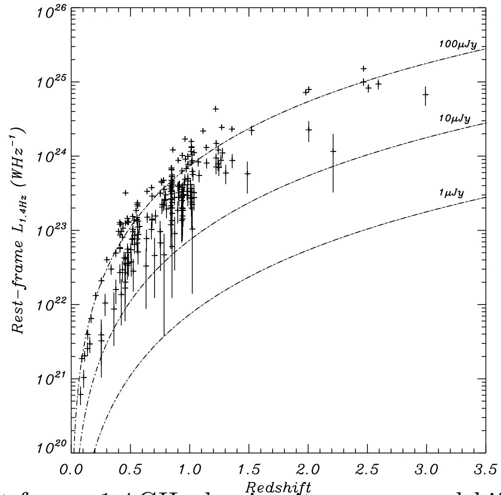

Figure 1. Rest-frame 1.4 GHz luminosity versus redshift for 212 24 μm *Spitzer* sources with redshifts and 1.4 GHz flux densities greater than 3 times the local map rms. All 1.4 GHz luminosities have measured within an aperture of radius 1.″5 centred upon the *Spitzer* MIPS 24 μm source position.

a completeness limit of 40 μJy beam^{-1} (5.3σ) within a 10 square arcminute field, using a 2″ beam. Muxlow *et al.* (2005) presented results from the combination of both this 42 hr VLA observation and an 18 day MERLIN integration at the same pointing centre ($\alpha = 12^{h}\,36^{m}\,49.^{s}4000$, $\delta = +62^{o}\,12'\,58.''000$ (J2000)). The combined MERLIN+VLA image has an rms noise level of 3.3 μJy per 0.″2 circular beam making it amongst the most sensitive high resolution radio image made to date. Full details of these observations and data reduction are presented in Muxlow *et al.* (2005) and Muxlow *et al.* (*this proceedings*).

In this proceedings we present some preliminary results from an extended analysis of these deep MERLIN+VLA radio observations of the HDF-N. This extended analysis uses the ancillary data obtained from the large multiwavelength Great Observatories Origins Survey (GOODS) which when combined with these extremely deep radio observations provide a clear insight into the characteristics of the microJansky radio source population. In these proceedings we briefly outline some of these preliminary results with particular emphasis on the radio detected *Spitzer* 24 μm sources within the 10×10 arcminute radio field. Additional further analysis of these radio observations, exploiting GOODS data-sets at X-ray and optical wavelengths are also presented in these proceedings by Richards *et al*, Thrall *et al* and Muxlow *et al.*. The results presented here are covered in more much detail in Beswick *et al. (in prep).*

2. Results & Discussion

2.1. Radio luminosities of 24 μm *Spitzer* sources

Within the entire field covered by the GOODS-N *Spitzer* 24 μm observations 1199 sources were identified with flux densities >80 μJy. However, for the purposes of comparing these 24 μm source with our radio data we have limited this sample to sources that are spatially coincident with the 8.5×8.5 arcmin^2 radio field.

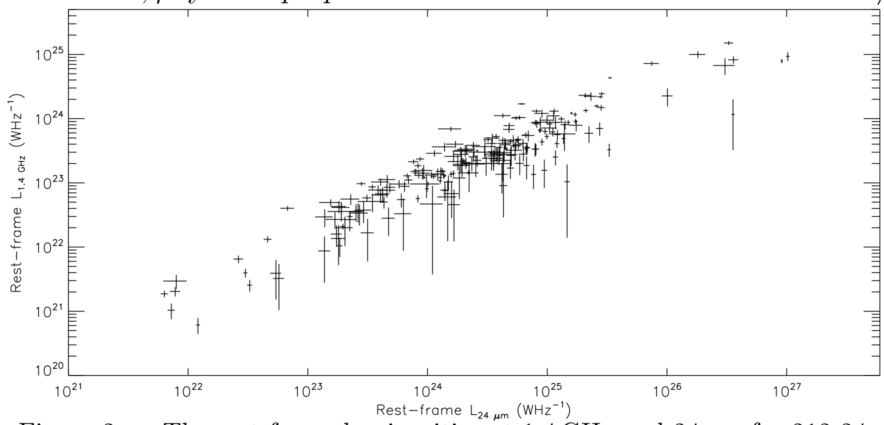

Figure 2. The rest-frame luminosities at 1.4 GHz and 24 μm for 212 24 μm *Spitzer* sources with redshifts. The rest-frame 1.4 GHz luminosities have been k-corrected (boosted) assuming a spectral index of 0.7. The rest-frame 24 μm luminosities have been corrected assuming an 'Arp220-like' SED. All errors shown are equivalent to 3-σ. All 1.4 GHz luminosities have measured within an aperture of radius 1.″5 centred upon the *Spitzer* MIPS 24 μm source position. Note that in the many of cases where sources with apparently low radio luminosity with respect to MIR luminosity are large nearby spirals with an optical extent larger than the 3″.

This sub-sample contains 377 *Spitzer* sources with 24 μm flux densities ranging from 80.1 to 1480 μJy.

Using the à prior positional information from the 24 μm *Spitzer* source catalogue, radio emission in our deep 8.′5×8.′5 MERLIN+VLA 1.4 GHz image was searched for within a series of eight, evenly-spaced, concentric rings with radii between 0.5 and 4 arcsec, at the position of each of the 377 24 μm sources. From the statistical analysis of the flux densities recorded within each of these annuli it has been shown that the majority (>90%) of the radio flux density of these sources is recovered within a radius of 1.″5 of the *Spitzer* source positions (Beswick it et al. in prep). A plot of the 1.4 GHz radio luminosity of all of the 24 μm sources with known redshift against their redshift is shown in Fig. 1. As can be seen in Fig. 1, the majority of the *Spitzer* sources lie between redshifts 0 and 3.5, and have 1.4 GHz radio flux densities of less than 100 μJy. From the radio morphological and spectral arguments of Muxlow *et al.* (2005) it has been shown that the faint radio source population (below 100 μJy) is dominated by star-forming galaxies. Similarly it can be expected that this MIR selected sample of radio faint intermediate and high redshift sources also primarily consists of star-forming galaxies. The *Spitzer* 24 μm versus 1.4 GHz luminosities of these sources is plotted in Fig. 2. In this figure it can be seen that as expected the MIR and radio luminosities of these star-forming galaxies are strongly correlated over ∼7 orders of magnitude: extending the correlation by several orders of magnitude to lower luminosities.

2.2. Radio sizes of 24 μm *Spitzer* sources

One massive advantage of these high resolution MERLIN+VLA radio observations is their sub-arcsecond angular resolution (0.″2 → 0.″5). At a redshift of

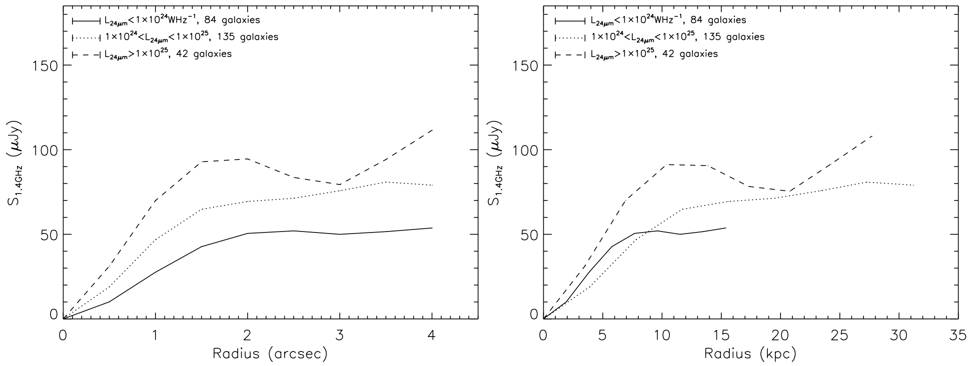

Figure 3. Radial plots of the mean cumulative enclosed 1.4 GHz flux density versus radius for the 261 24 μm *Spitzer* sources with redshifts. The averaged source flux densities within enclosed radii (plotted against angular and linear sizes) are shown for sub-sets of these sources binned with respect to their 24 μm luminosity. Each sub-set has been ascribed the mean redshift sources in each bin.

$\sim$0.7 the resolution of these radio observations is a few kpc. This angular resolution is adequate to resolve the galactic scale radio structure of sources out to redshifts of a few. Figure 3 shows the cumulative radial profiles of the 1.4 GHz radio emission of the 24 μm *Spitzer* sources within the $8'.5\times8'.5$ field binned by their 24 μm luminosities. As can be seen in the left-hand plot the majority of the radio flux density for all of these sources is enclosed with in a radius of 1.5–2 arcseconds. Converting these angular sizes to the galaxies linear extent (Fig 3 *right-hand plot*) shows that, on average, the lower luminosity MIR sources (solid line) have radio emission on sub-galactic scales, extending out to radii of $\sim$7 kpc, consistent with radio starburst emission from within these galaxies. In comparison the radio emission from the more luminous MIR sources, whilst still on galactic scales, appears to extend to larger radii ($\sim$10-15 kpc).

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