The Star Formation History of the Universe as Revealed by Deep Radio Observations

N. Seymour\textsuperscript{1}\textsuperscript{*}, T. Dwelly\textsuperscript{2}, D. Moss\textsuperscript{2}, I. McHardy\textsuperscript{2}, A. Zoghbi\textsuperscript{2,3}, G. Rieke\textsuperscript{4}, M. Page\textsuperscript{5}, A. Hopkins\textsuperscript{6} and N. Loaring\textsuperscript{7}

\textsuperscript{1}Spitzer Science Center, Caltech, 1200 East California Boulevard, Pasadena, CA 91125, USA.
\textsuperscript{2}School of Astronomy & Astrophysics, University of Southampton, Highfield, Southampton, SO17 1BJ, UK.
\textsuperscript{3}Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK.
\textsuperscript{4}Steward Observatory, Tucson, USA.
\textsuperscript{5}Mullard Space Science Laboratory, UCL, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK.
\textsuperscript{6}University of Sydney, Australia.
\textsuperscript{7}SALT, PO box 9, Observatory, 7925, South Africa.


draft 19th February 2008

ABSTRACT

Discerning the exact nature of the sub-mJy radio population has been historically difficult due to the low luminosity of these sources at most wavelengths. Using deep ground based optical follow-up and observations from the Spitzer Space Telescope we are able to disentangle the radio-selected Active Galactic Nuclei (AGN) and Star Forming Galaxy (SFG) populations for the first time in a deep multi-frequency VLA/MERLIN Survey of the \textsuperscript{13}H\textsuperscript{XMM-Newton/Chandra Deep Field. The discrimination diagnostics include radio morphology, radio spectral index, radio/near-IR and mid-IR/radio flux density ratios. We are now able to calculate the extragalactic Euclidean normalised source counts separately for AGN and SFGs. We find that while SFGs dominate at the faintest flux densities and account for the majority of the up-turn in the counts, AGN still make up around one quarter of the counts at \(\sim 50\ \mu\text{Jy} \ (1.4\ \text{GHz})\). Using radio luminosity as an unobscured star formation rate (SFR) measure we are then able to examine the comoving SFR density of the Universe up to \(z = 3\) which agrees well with measures at other wavelengths. We find a rough correlation of SFR with stellar mass for both the sample presented here and a sample of local radio-selected SFGs from the 6df-NVSS survey. This work also confirms the existence of, and provides alternative evidence for, the evolution of distribution of star formation by galaxy mass: “down-sizing”. As both these samples are SFR-selected, this result suggests that there is a maximum SFR for a given galaxy that depends linearly on its stellar mass. The low “characteristic times” (inverse specific SFR) of the SFGs in our sample are similar to those of the 6dF-NVSS sample, implying that most of these sources are in a current phase of enhanced star formation.

Key words: radio continuum: galaxies, galaxies: evolution, starburst

1 INTRODUCTION

Whilst observations of powerful, radio-loud Active Galactic Nuclei (AGN) were an early probe of the distant Universe (see [Stern & Spinrad 1999, for a summary]), starburst galaxies are three or more orders of magnitudes less luminous at radio wavelengths and hence difficult to observe at large distances. However the deepest radio surveys at 1.4 GHz now reach an rms below 10 \(\mu\text{Jy}\) ([Richards 2000, Seymour et al 2004, Biggs & Ivison 2006, Fomalont et al 2006, etc.]). These deep radio observations reveal a (very well characterised) up-turn in the Euclidean normalised sources counts below 1 mJy above that predicted from the extrapolation of the AGN counts measured at brighter flux densities. This up-turn has been attributed to the emergence of a star forming galaxy (SFG) population, requiring strong evolution of the SFG radio luminosity function ([Rowan-Robinson et al 1993, Hopkins et al 1993, Seymour et al 2004, Moss et al 2007], although some authors argue that there is a significant contribution due to rel-
\textbf{2 N. Seymour et al.}

\begin{quote}
"relatively weak radio AGN (Simpson et al. 2006; Huynh et al. 2007; Barger et al. 2007)."
\end{quote}

\begin{quote}
"Determining the nature of individual radio sources has remained difficult due to their low luminosities at other wavelengths. Discrimination between radio-selected SFGs and AGN in these deep surveys would, for example, allow an independent measure of the star formation history of the Universe as star formation rate (SFR) is directly related to radio luminosity for galaxies with weak or no AGN radio emission (Condon 1992). The comoving SFR density (SFRD) has been determined previously from deep radio data out to $\sim 1.6$ (Haarsma et al. 2000), but the study presented here offers several improvements and advantages, noticeably a more robust and systematic discrimination between AGN and SFG, the use of more accurate redshifts, an extension to higher redshift and a larger area/sample size by a factor of $\sim 5$.
\end{quote}

\begin{quote}
"While radio surveys have not traditionally been used to determine SFRs in the distant Universe, other methods have their limitations. The far-IR and sub-mm wavelength range is limited by the relatively poor sensitivity and angular resolution of current instrumentation and telescopes. The mid-IR, whilst very sensitive, is not as reliable a tracer of SFR at high redshift as the far-IR and sub-mm (e.g. Papovich et al. 2003). UV emission from young massive stars can easily be obscured by dust, but the extrapolation of models derived from local galaxies likely break down for the more luminous galaxies, $> L_*$, found in deep optical surveys. Furthermore, the rest-frame UV is redshifted across a large wavelength range (UV/optical/near-IR) at cosmological distances so different detectors are needed to trace the UV at different redshifts. Determination of the SFR from optical emission lines is also affected by obscuration and shifting to longer wavelengths and hence in and out of observable wavelength windows. The optical emission lines can also suffer from absorption by dust. X-ray emission associated with star formation (e.g. from binary stars) is intrinsically weak and is subject to varying degrees of photoelectric absorption. Even at the faintest X-ray fluxes reached in the CDFN ($\sim 10^{-17}$ erg cm$^{-2}$ s$^{-1}$), the source counts are dominated by AGN (Bauer et al. 2004). Given that forthcoming radio facilities (e.g. EVLA, e-MERLIN, LOFAR, ASKAP, and eventually the SKA) will reach many orders of magnitude deeper than the current deepest radio survey, and will be able to detect star forming galaxies out to the era of re-ionization ($z \lesssim 7$), it is timely to consider how to characterise the emission from faint radio sources and which supporting data are the most valuable.
\end{quote}

\begin{quote}
"We make an important distinction here between radio indicators of an AGN and non-radio indicators of an AGN. We need to separate the radio sources into those whose radio emission is AGN dominated and those that are consistent with being dominated by star formation. By AGN powered indicators we mean some measure that indicates that the radio emission from a galaxy is dominated by accretion onto a super-massive black hole and/or from associated jets and lobes (i.e. radio-loud AGN). We assume, for simplicity, that the dominant power in most sources is either from an AGN or from star formation, but otherwise make no a priori assumptions about the sources, e.g. the SED. The radio AGN indicators we use in this paper are radio/near-IR flux density ratio, mid-IR/radio flux density ratio, radio morphology and radio spectral index. We do not include non-radio AGN indicators, e.g. classical methods like optical/IR emission lines, optical morphology, X-ray observations etc. and methods from recent results with the Spitzer Space Telescope based on mid-IR SEDs (e.g. Donley et al. 2003; Stern et al. 2003; Lacy et al. 2003). As these non-radio indicators tell us nothing directly about the nature of the radio emission we do not use them in our discrimination methods. A comparable philosophy was previously adopted by Muxlow et al. (2005).
\end{quote}

\begin{quote}
"In this paper we will present our method for classifying the faint radio sources and examine the properties of the SFG population. The radio, optical and IR observations are summarised in section 2. The various methods of discriminating between AGN and SFGs are presented in section 3. In section 4 we present the Euclidean normalised source counts separately for AGN and SFGs for the first time. In section 5 we study the general properties of the radio-selected SFG population, present the comoving SFR density of the Universe up to redshift $\sim 3$ derived from our data, examine the distribution of star formation with host galaxy stellar mass and derive characteristic times. We conclude this article in section 6. Throughout we use a concordance model of Universe expansion, $\Omega_M = 1 - \Omega_\Lambda = 0.3$, $\Omega_\Lambda = 1$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2003). Magnitudes are AB unless otherwise stated.
\end{quote}

\begin{quote}
\textbf{2 THE DATA}
\end{quote}

\begin{quote}
The 13$^\text{th}$ XMM-Newton/Chandra Deep Survey field presents us with a unique data set for performing a radio-based SFG/AGN separation of radio sources. This field, centred at $13^\text{h} 34^\text{m} 37^\text{s}$ + $37^\circ 54^\prime 44^\prime$', was the location of one of the deepest ROSAT surveys (M'Hardy et al. 1998), and lies in a region of extremely low Galactic absorption ($N_H \sim 6 \times 10^{19}$ cm$^{-2}$).
\end{quote}

\begin{quote}
\textbf{2.1 The radio data}
\end{quote}

\begin{quote}
\textbf{2.1.1 The VLA 1.4 GHz observations}
\end{quote}

\begin{quote}
The 13$^\text{th}$ XMM-Newton/Chandra deep field was observed by the VLA at 1.4 GHz for 14 hrs in A-array in August 1996 and 10 hrs in B-array in November 1995. A catalogue of 449 sources above 30 $\mu$Jy (4 $\sigma$ detection limit) in a 30 arcmin diameter circular field of view (0.196 deg$^2$) was obtained with a resolution of 3.3 arcsec. The Euclidean normalised source counts, corrected for the incompleteness of the catalogue due to instrumental effects, were presented in Seymour et al. (2004, hereafter S04). The 449 sources detected at 1.4 GHz with the VLA constitute the parent sample on which this work is based. In contrast to S04 we use the peak flux density instead of total flux density for sources that are significantly resolved and at low S/N as the peak flux is a better measure of the true flux in these cases.
\end{quote}

\begin{quote}
The size of this sample (in terms of area and number of sources) is well positioned between those fields of the similar area but are slightly deeper (by $\sim 40\%$ e.g. the Lockman Hole and the HDFN, Biggs & Ivison 2006) and those of larger area (e.g. AEGIS and COSMOS, Ivison et al. 2007, Schinnerer et al. 2007), but which are less deep by $\sim 40\%$.
\end{quote}
2.1.2 The MERLIN 1.4 GHz observations

The 13th field was observed with Multi-Element Radio-Linked Network in April 1999. Due to the smaller field of view, 10 arcmin, four MERLIN pointings were used to cover most of the VLA field of view. MERLIN has a higher resolution, 0.2 arcsec, than the VLA due to its greater maximum base-line. We used the parent catalogue as a detection list and only imaged the positions around known sources (including bright sources not in the principle VLA or MERLIN field of view). We made MERLIN images for all VLA detections with $S_{1.4} > 72 \mu$Jy that lay inside the MERLIN coverage. These images were combined by first making maps without the beam deconvolved and beams around each source in the sky plane, then averaging the maps and beams before deconvolving the average beam from the average map as described by A. Zoghbi et al. (in prep.) The combination of datasets from different telescope arrays is non-trivial as the four MERLIN pointings are offset from the VLA phase center and both the VLA and MERLIN images suffer from radial smearing. However for sources in the parent sample having flux densities above $\sim 100 \mu$Jy, and that are favourably positioned, we can make high-resolution maps from combined MERLIN and VLA data.

2.1.3 The VLA 4.8 GHz observations

The 13th field was observed with the VLA at 4.8 GHz in April 1991. The observations cover the whole field of view of the 1.4 GHz data, 30 arcmin (observations originally designed to match the ROSAT field of view [Hardy et al. 1998]) with 51 separate pointings. The observations reach 33 $\mu$Jy rms, and were performed in VLA D-array hence the restoring beam is 14 arcsec, around a factor four greater than the 1.4 GHz observations. From the catalogue of [Seymour 2002] we find 45 sources with flux densities $> 4 \sigma$ and within the 30 arcmin diameter field of view of the 1.4 GHz observations. Of these 45 sources have counterparts in the 1.4 GHz catalogue within 7 arcsec and hence we can calculate their $1.4 - 4.8$ GHz spectral indices. We define the radio spectral index, $\alpha$, by $S_\nu \propto \nu^\alpha$, and hence $\alpha = -1.85 \log_{10}(S_{1.4}/S_{4.8})$. We use total, rather than peak, flux densities when calculating the radio spectral index. In our earlier study (S04), we made tapered maps of the 1.4 GHz data but we did not find significant extended radio emission that could affect the calculated spectral indices. There is one instance where two nearby 1.4 GHz sources (separated by 20 arcsec) are matched to a single 4.8 GHz source and therefore we cannot calculate the spectral indexes separately for these two sources.

2.2 Optical, near-IR and mid-IR data

2.2.1 Optical and near-IR data

We have obtained imaging in many bands from the near-UV to near-IR over recent years: $u^*$, $g'$, and $i'$-band from MegaCam/CFHT, $B$, $R$, $I$ and $z'$-band from SuprimeCam/Subaru, $Z$-band from WFC/INT, $J$-band from WIRC/Palomar, $H$-band from WIRC/C/CFHT, and $K$-band from WFCAM/UKIRT. This imaging covers the entire parent sample bar the WIRC J-band (which covers approximately 3/4 of the survey area), and has been supplemented by hundreds of optical spectra of the counterparts to our radio and X-ray sources. Of our parent sample 164/449 currently have redshifts determined from optical spectroscopy.

2.2.2 Mid-IR data

The 13th field was observed by the IRAC [Fazio et al. 2004] and MIPS instruments [Rieke et al. 2004] on board the Spitzer Space Telescope [Werner et al. 2004] in July 2005 as part of MIPS instrument team GTO time (PI G. Rieke, program identification number 81). A strip of $\sim 0.5 \times 1$ deg containing the 13th field was imaged by both instruments. The IRAC data consisted of observations with all four channels (3.6, 4.5, 5.6 and 8.0 $\mu$m) reaching $1 \sigma$ flux density limits of 0.7, 1.2, 7.2 and 7.6 $\mu$Jy respectively. These values represent the limiting flux density of a point source for which we can make a flux measurement in a 3.8 arcsec diameter aperture with $> 1\sigma$ accuracy. Most, 388/449 (77%), of our parent sample were detected in at least the 3.6 $\mu$m channel. The 24 $\mu$m data was taken as part of a simultaneous scan map in each of the three bands (24, 70 and 160 $\mu$m) reaching a $3 \sigma$ detection limit of 98 $\mu$Jy in a 10.5 arcsec aperture. We found 330/449 (73%) of our parent sample had 24 $\mu$m counterparts. We do not use the 70 and 160 $\mu$m data here as they are not sensitive enough to provide information on most of the radio sources, and then only those at low redshift.

2.2.3 Photometric Redshifts

We have used our multi-band near-UV to near-IR together with IRAC 3.6, 4.5 and 5.8 $\mu$m data to calculate photometric redshifts for the optical counterparts to our radio sources. Full details of this process will be presented in Dwelly et al. (in prep. hereafter D08), but here we give a short summary. Initial catalogues were generated independently for each optical, near-IR and mid-IR waveband using SExtractor [Bertin & Arnouts 1996]. These initial catalogues are then combined into a single “master” catalogue containing only unique detections. Aperture photometry is carried out in each waveband at the locations of each master catalogue source. In the optical/near-IR bands we used a 3 arcsec diameter aperture for bright sources ($i' < 20$), and a 2 arcsec aperture for fainter sources to improve S/N. In the IRAC bands a 5.8 arcsec diameter aperture was employed. Appropriate aperture corrections are applied given the different point spread functions in each waveband [Gawiser et al. 2006]. We match optical/near-IR counterparts to the parent radio sample are by searching for all objects in the “master” catalogue lying within 1.5 arcsec of the peak of the radio emission. Where available we use the high resolution images from combined MERLIN+VLA maps to determine the correct optical counterparts. We examine the optical and radio images for sources with more than one counterpart, and manually choose the most appropriate object. We then used the publicly available Hyperz code [Bolzonella et al. 2000] to determine photometric redshifts for each source from their multi-band aperture photometry. Only the wavebands shortward of 5.8 $\mu$m were used to determine photometric redshifts in order to avoid complications with PAH features. We used
the standard set of synthetic evolving galaxy templates supplied with Hyperz. To ensure reliability, we ignore the photometric redshifts calculated for all radio sources detected with $>3\sigma$ significance in fewer than 4 wavebands. Hence, 60 radio sources from our parent sample have no photometric redshift information including 31 with no counterparts detected in any optical, near-IR or mid-IR waveband. Most of the other 29 sources are detected only in the K-band data and/or the two shorter wavelength IRAC channels, and hence the derived photometric redshifts have very large uncertainties. We consider the likely nature of these objects in section 3.6.1.

2.3 Local 6dF-NVSS comparison sample

To illustrate our discrimination techniques we use the 6dF-NVSS sample of local spectroscopically identified radio sources from [Mauch & Sadler 2007]. These authors identified $\sim 8000$ radio sources from the 1.4 GHz NRAO VLA Sky Survey (NVSS, Condon 1992) in the Second Incremental Data Release of the 6 degree Field Galaxy Survey (6dFGRSD2) with galaxies brighter than $K = 12.75$ (Vega) from the 2MASS Extended Source Catalogue. This sample covers about 17% of the sky and includes galaxies across $0.003 < z < 0.3$. [Mauch & Sadler 2007] discriminated between AGN and SFGs using emission and absorption features in the 6dF spectra and derived local luminosity functions for both populations using the [Saunders et al. 1990] form of the luminosity function (LF) which is commonly used at long-wavelengths (i.e. mid-IR and longward). Their sample has also been cross-matched with the IRAS Faint Source Catalogue providing fluxes at 12, 25, 60 and 100 $\mu$m which they use to confirm the radio-IR correlation. The [Mauch & Sadler 2007] catalogue provides us with a local reference sample of SFGs with known radio, IR and K-band flux densities (from which we can derive SFRs and stellar masses) to which we can compare our results from higher redshift.

3 RADIO-BASED EMISSION DIAGNOSTICS

Here we present four radio emission diagnostics which directly probe the physical origin of the radio luminosity; two of these are purely from the radio data (radio spectral indices, morphology), and two involve comparisons with observed flux densities at other wavelengths (mid-IR and near-IR) as a function of redshift. These diagnostics are mostly positive AGN discriminators, i.e. they generally imply that the radio emission of a source is very likely powered by AGN emission and not star formation. We do not include the obvious radio luminosity discriminator, where a radio luminosity $>10^{25} \text{WHz}^{-1}$ would imply an unphysical SFR of $\sim 5000 \text{M}_\odot \text{yr}^{-1}$, as those eight sources clearly above this luminosity are flagged as AGN by one or more of the other methods below and potentially such objects do exist in small numbers at high redshift.

We give the number of sources from our parent sample for which each of our AGN/SFG discriminators is applicable in Table 1 along with a short comment of why they apply to only such a number. We discuss the implications of these selection functions in §3.5.

### Table 1. Number of sources from our parent sample for which each SFAGN discrimination method is applicable. We list discrimination method, the number of sources which it is applicable to and the reason why.

| Discrimination | #   | Limitation of method               |
|----------------|-----|-----------------------------------|
| morphology     | 127 | brightest sources only and coverage |
| spectral index | 45  | brightest sources only             |
| $S_{24\mu m}/S_{1.4GHz}$ | 445 | limited by 24 $\mu$m coverage     |
| $S_{1.4GHz}/S_{2.2\mu m}$ | 449 | applies to all sources             |

3.1 Radio morphology

Only six sources from the parent sample show the classical unambiguous AGN signature of a double lobed, FR2 morphology (i.e. [Fanaroff & Riley 1974]) in our 3.3 arcsec resolution imaging. For other extended VLA sources there is not enough detail to distinguish between a clear AGN morphology and extended, galaxy scale emission from star formation. Additionally we include results of the combined MERLIN+VLA(A-array) maps at 1.4 GHz (A. Zoghbi et al., in prep.) which have a resolution of 0.5 arcsec. These results are limited to the brighter objects from our master sample due to the sensitivity of our MERLIN images, and also the inner $\sim 20$ arcmins covered by the four MERLIN pointings. We are therefore able to make combined maps for 127 sources. Many show clear AGN jet/lobe morphology including the six sources flagged as AGN from the lower resolution VLA images. The other sources show either a very compact, unresolved morphology or are extended on $\sim 1$ arcsec scales, often almost completely resolved out due to the lack of sensitivity of MERLIN to extended structure. Although the unresolved sources do not have significantly constrained brightness temperatures ($\geq 10^{24}$K) this compactness is most likely due to an AGN (e.g. [Muxlow et al. 2003]), but a small chance remains that they could be due to nuclear starbursts. The sources with extended emission over the galaxy which is often completely resolved out must be from star formation occurring throughout the galaxy. Hence, the MERLIN+VLA images show that 42/127 sources are very likely to be AGN.

3.2 Radio spectral indices

Using our 4.8 GHz data ([Seymour 2002]) we have radio spectral indices for 45 sources in our sample. These are among the brightest sources in our sample as the 4.8 GHz rms of 30 $\mu$Jy corresponds to $\sim 70$ $\mu$Jy at 1.4 GHz assuming $\alpha_{1.4} = -0.8$. Radio emission from star formation, due to synchrotron radiation, will generally have a spectrum with a slope in the range $-0.5 \lesssim \alpha_{1.4} \lesssim -1.0$ ([Thompson et al. 2000]). Radio sources with spectral indices steeper than $\alpha = -1$ are typically targeted as high redshift radio galaxies. Therefore any radio sources with spectral indices not in the range $-0.4 \lesssim \alpha_{1.4} \lesssim -1.1$ (allowing for the errors in the flux densities) we flag as having AGN powered radio emission. We find 31 sources have spectral indexes not in this range (i.e. with $\alpha_{1.4} \geq -0.4$ or $\alpha_{1.4} \leq -1.1$).

This diagnostic is particularly powerful as it is relatively insensitive to redshift; e.g. [Klamer et al. 2006] find that 90% of a sample of high redshift AGN have radio spectra
3.3 Radio to near-IR flux density ratios

"Radio-loudness" is another classical discriminator of radio-luminous AGN (Kellerman et al. 1989) and traditionally based on radio to optical (observed or rest-frame) flux density ratio. More recently radio-loudness has been defined in terms of absolute radio luminosity (e.g. Miller et al. 1995, $L_{1.4\text{GHz}} \gtrsim 10^{25} \text{W Hz}^{-1}$), but this diagnostic would only apply to eight of our parent sample and those have already been flagged as an AGN by one or both of the previous two diagnostics. The original definition of radio loudness was based on B-band observations, but given that at the redshifts in question, 0 $\leq z \leq 4$, this band quickly starts sampling below the 4000 Å break where variations in star formation rate and absorption by dust have a strong effect, we chose to use a longer wavelength band. In fact the only band short-ward of the mid-IR which remains longward of the 4000 Å break up to $z \sim 4$ is K-band. Our K-band data are particularly deep: $K = 22.6$ (3σ limit).

In keeping with our philosophy stated in the introduction, where we make no assumptions about the observed SED, we plot the observed flux density ratios against redshift. Given that we do not know the nature of each radio source beforehand, we can only plot the un-k-corrected flux density ratios and compare them with tracks of different AGN and starburst galaxies. This approach avoids making any a priori assumptions about the nature of each source. In Figure 1(a) we present the 1.4 GHz to K-band flux density ratio against redshift. We plot the tracks of two star forming galaxies which have no strong AGN component. These are LIRG and ULIRG templates made from average composites from fits to about a dozen LIRGs and ULIRGs with very high fidelity observations. From 5 – 35 μm they are based on Spitzer IRS long low spectra. For 1 – 5 μm, the templates are built from stellar population models, with overall slopes constrained by large beam IRAC and 2MASS photometry. The radio regime was determined with data from Condon et al. (1991). The corresponding SFRs of these two templates are approximately $\sim 10$ and $\sim 100 M_{\odot}yr^{-1}$ respectively. We also plot the tracks of classical ‘radio-loud’ and ‘radio-quiet’ QSOs from the templates of Elvis et al. (1994).

Figure 1(a) shows several clear radio-loud AGNs with flux density ratios similar to or greater than the radio-loud QSO template track. We can use this plot to define a locus where a radio source will unambiguously be identified as an AGN. We decide to take a cut 5σ above the higher SFG track (the ULIRG one) where σ comes from taking an uncertainty of 20% in the radio flux density and 20% in the K-band magnitude. We emphasise that these uncertainties are extremely conservative and that the majority of radio sources will have much smaller uncertainties, but we are also allowing for the uncertainty in the SEDs used for the template tracks. Combining these uncertainties we get a 5σ cut of $0.6 \text{dex} = \sqrt{0.2^2 + 0.2^2}/\ln(10)$.

We note that all bar one of the sources with unknown redshifts are well above our AGN/SFG discrimination line at almost all redshifts and hence are most likely all obscured AGN at high redshift (see §3.5.3 for further discussion of these sources).

3.4 Radio to mid-IR flux density ratios

The correlation of the radio and far-IR luminosities of star forming galaxies is well established over five orders of magnitude (Yun et al. 2001) and is one of the tightest results in astrophysics. The continuation of this relationship in the mid-IR and to $z \gtrsim 1$ is also fairly well established (Garrett et al. 2002, Appolon et al. 2004). Furthermore we show in the Appendix that the total-IR to radio luminosity relationship does continue to high redshifts for ULIRGs. This relationship can be used as another clear discriminant of radio loud AGN; all objects with a relative “radio-excess” are very likely to be AGN.

Spitzer provides comparably deep IR observations to the radio which allows comparison of the IR properties of the sub-mJy radio population. We choose to use the 24 μm band of the MIPS instrument as it is more sensitive than the 70 μm band with a 3σ detection limit of 98 μJy compared to 3σ ∼ 3 μJy at 70 μm. This 24 μm detection limit should be sufficient to detect all the luminous starburst galaxies ($L_{24\mu m} \gtrsim 3 \times 10^{10} L_\odot$) which we could detect at radio wavelengths out to $z \sim 1$ and most starburst galaxies at $z > 1$, given the nominal 1.4 GHz detection limit of our parent sample.

In Figure 1(b) we plot the distribution of mid-IR to radio flux density ratios, $S_{24\mu m}/S_{1.4\text{GHz}}$, against redshift for sources in our sample. We compare this distribution to redshifted starburst and AGN templates tracks in a similar way to section 3.3. On the whole a large number of 24 μm detected sources follow the SFG template tracks suggesting that star forming galaxies make up a significant fraction of the sub-mJy radio population. There are many obvious “radio-excess” and a few “IR-excess” sources which are both likely to harbour AGN. The radio-excess sources are likely to host AGN due to their radio-loud nature. The IR-excess sources are likely to host radio-quiet AGN with hot dust dominating in the mid-IR, i.e. radio-quiet obscured AGN such as those found by Lacy et al. (2004), but with moderate amounts of star formation dominating the radio emission. These “IR-excess” sources likely explain the high the mid-IR to radio flux density ratio seen in Beswick et al. (2008) due to k-correction effects to the observed ratio.

As in the previous section we use a 5σ cut-off below the more extreme starburst. We again get a cutoff value of $5σ = 0.6 \text{dex}$ from assuming a median 20% uncertainty in both the 1.4 GHz and 24 μm flux density. This cut also allows for uncertainty in the SED tracks.
Figure 1. (a) 1.4 GHz to near-IR flux density ratio plotted against redshift and (b) 24 µm to 1.4 GHz flux density ratio plotted against redshift. Filled symbols have spectroscopic redshifts and open symbols have photometric redshifts. The large blue symbols are those radio sources confirmed as AGN from their morphology (triangles), spectral index (squares) or both (stars). We show the location of the flux density ratios of the local 6dF-NVSS sample with green dots. The tracks of star forming galaxies with luminosities over the range of interest are marked: LIRG (red dotted lines), ULIRG (red dot-dashed lines). See text more discussion of the templates used. We also over-plot the tracks of a radio-loud (blue dash-dot-dot-dotted lines) and a radio-quiet QSO (blue dashed lines) from Elvis et al. (1994). The cut-off (solid black lines) in both cases is chosen to be 0.6 dex (= 5σ) above or below the more extreme of two the SFG tracks. Sources without known redshifts are plotted at z = 0.

Table 2. Results of the discrimination of sub-mJy radio sources. The raw numbers are presented for each galaxy type as well as the number of sources with spectroscopic, photometric or unknown redshifts. We also present the number of different sources corrected for incompleteness in the radio survey and the percentage of the total number of sources.

| Classification | N    | Nspec/Nphot/N? | Ncorr | Percentage |
|----------------|------|----------------|-------|------------|
| AGN            | 178  | 31/88/59       | 244   | 35.8%      |
| SFGs           | 269  | 131/138/0      | 436   | 64.0%      |
| Stars          | 1    | 1/0/0          | 1     | 0.1%       |

3.5 Results of AGN/SFG discrimination

Using the above four discriminators we can discriminate the AGN from the SFGs on a statistical basis. Although most of these discriminators are mainly just positive AGN identifiers we can be reasonably confident that we have removed nearly all the AGN, at least statistically. In fact, 58% of the sources flagged as AGN are done so by two or more discriminators. We find that 178/449 sources show clear indications that their radio emission is due to AGN activity. One radio source is, surprisingly, identified as a star from optical spectroscopy. These results are summarised in Table 2 along with the incompleteness corrected number and percentage. This incompleteness factor is a correction for the decrease in the sky area probed at faint fluxes due to the decrease in sensitivity of our radio map away from the pointing centre.

We look at the break down of radio AGN classification in Table 3. We find that the two most effective methods are the flux density ratios which each account for ∼ 60 – 80% of the sources classified as AGN, but only overlap for ∼ 44% of the total. Hence, together they account for almost all, 90% (160/178), of the radio sources classed as AGN. The sensitivity of our K-band and 24 µm observations are generally deep enough that we are not biased by non-detections in these bands as that would put a source clearly out of the SFG regime, except possibly for the mid-IR/radio flux density ratio and radio/near-IR flux density ratio. The diagonal represents the number of sources classified as AGN by just the corresponding discriminator. The lower left of the table, below the diagonal, gives the number of sources flagged as AGN for a particular combination of discriminators.

Table 3. Break-down of the number of radio sources classified as AGN by each of our four discrimination methods. The columns and rows correspond to the four methods of AGN/SFG discrimination used in sections 3.1 to 3.4: radio morphology, radio spectral index, mid-IR/radio flux density ratio and radio/near-IR flux density ratio. The diagonal represents the number of sources classified as AGN by just the corresponding discriminator. The lower left of the table, below the diagonal, gives the number of sources flagged as AGN for a particular combination of discriminators.

| classification | morphology | α | mid-IR | near-IR |
|----------------|------------|---|--------|---------|
| morphology     | 44         | - | -      | -       |
| α              | 12         | 32| -      | -       |
| mid-IR         | 27         | 16| 102    | -       |
| near-IR        | 30         | 15| 79     | 137     |
were changed so as to classify more radio sources as SFGs than AGN, we found a swing (i.e. change in AGN/SFG distribution) of 4.2% in the number of SFGs from the parent sample and when changed so as to increase the number of AGN we found a swing of 5.6%. These values are on par with the Poisson statistics expected from dividing the parent sample into two roughly equal populations (~6%). It is possible that some or many of the SFGs may contain AGN, but that these AGN do not contribute strongly to the radio emission, e.g. the “IR-excess” sources in Figure 1(a). It is also possible that some radio SFG are really radio AGN, especially as some of the discrimination methods do not work so well at faint flux densities. The possible number of AGN interlopers is roughly equal populations (~σ).

Figure 2. The 1.4 GHz radio flux density plotted against I-band magnitude of all our sources separated into AGN (blue squares) and SFGs (red triangles). Radio sources undetected in I-band above 3σ are marked as upper limits at I ~ 25.9. The lines represent the median I-band magnitude for the SFGs (dashed line) and AGN (dotted line) as a function of flux density.

3.5.1 Radio sources with faint optical or near-IR detections

Determining the nature of faint radio sources with weak or no detections at other wavelengths is naturally difficult. We have 60 sources from the parent sample where we are not able to determine a redshift, spectroscopic or photometric. In fact, 31 of these sources have no detections, > 3σ, at any other wavelength. The radio sources with unknown redshifts are included in Figure 1(b) at z = 0, either as upper/lower limits or detections. Their positions in these plots suggest that they would be mainly classified as AGN whatever their redshift, especially in Figure 1(a), where our AGN/SFG cutoff has only a weak dependence on redshift.

We considered the possibility that they are low mass SFGs (their optical faintness implying they are obscured, type 2 AGN). They are likely to be similar to the classical high redshift radio galaxies, but less luminous (i.e. in the log(L_{1.4 GHz}/W Hz^{-1}) ≲ 26 range Sajina et al. 2007).

4 RADIO SOURCE COUNTS BY TYPE

The total Euclidean normalised radio source counts from the 13^h field were presented in S04 where we found the counts to be in agreement with the many other published counts at similar flux densities. However, a scatter between the different counts from different surveys was found which was particularly strong around 200 – 300 μJy with the counts from the HDF-N (Richards 2000) being significantly low. This scatter was attributed to sample variation due to large scale structure. An independent reanalysis of the HDF-N counts by Biggs & Ivison (2004) revised them upwards, but a smaller scatter due to sample variance nevertheless remains.

4.1 Radio source counts at z = 0

We present the radio flux density versus I-band magnitude distribution in Figure 2. This plot shows that the brightest radio sources (log(S_{1.4 GHz}/μJy) > 2.5) are mainly AGN, but with a population of star forming galaxies coming in at lower radio flux densities and brighter optical magnitudes than the AGN. This result also suggests that the optically un-identified and faint sources are most likely to be AGN (e.g. at high redshift and obscured). At z > 1 sources would appear compact enough that we should detect intrinsically bright, but low surface brightness galaxies at the depths of our data which have a typical seeing of 1 arcsec. Below z = 2.2 we expect to detect all sources with log(\frac{L_{21cm}}{L_\odot}) > 10, in our near-IR or IRAC data, corresponding to quite low stellar masses (i.e. log(M/L_\odot) ~ 10 depending on the exact mass-to-light ratio). We plot the median I-band magnitude of the SFGs and AGN in Figure 2 which both decrease toward fainter radio flux densities. We believe the parent sample to be reliable as we would expect 0.03 of sources to be spurious in pure Gaussian noise, although the noise in radio maps is not completely Gaussian. In S04 we carefully examined visually all the sources to remove those that were clearly due to artifacts from the radio reduction. We can’t rule out the possibility that one or two sources at low S/N and with no optical remain spurious, but our results would not change significantly if this were the case.

Figure 2 shows that the optical properties of the parent sample do change with radio flux density contrary to the results of Simpson et al. (2006) who do not see a decrease in the median magnitude with decreasing radio flux density. The difference between the results here and those of Simpson et al. (2006) can mainly be explained by the fact we have deeper radio data (by 0.5 dex) and the trend we see is strongest at the faintest flux densities. Results at the highest flux densities are likely affected by small number statistics. Hence, we conclude that most, if not all, of the radio sources with optically very faint counterparts are high redshift radio galaxies (their optical faintness implying they are obscured, type 2 AGN). They are likely to be similar to the classical high redshift radio galaxies, but less luminous (i.e. in the 24 ≤ log(L_{1.4 GHz}/W Hz^{-1}) ≤ 26 range Sajina et al. 2007).
We can now re-calculate the source counts at 1.4 GHz separately by type, AGN and SFG, correcting for incompleteness of the radio survey as in S04. As in the original presentation of these counts we only take sources above 5σ. Uncertainties include Poisson statistics and sample variance (which we discuss in § 5.2).

The counts by type are presented in Table 4 and Figure 3. We overlay some models for the AGN and SFG contribution to the radio source counts. We show the SFG and AGN model from S04 and the AGN model courtesy of M. Jarvis and R. Wilman, based on Jarvis & Rawlings (2004). The S04 AGN model is basically an extrapolation from higher flux densities of the models used in Dunlop & Peacock (1990) and Hopkins et al. (1998) and hence not necessarily valid for these low flux densities although they were the best available at the time. The Jarvis AGN model matches the observed AGN counts well and includes a component of radio quiet QSOs based on the evolution of the X-ray AGN luminosity function. This model appears to follow reasonably well the increase in AGN above the extrapolation of older models, like that used in S04, from higher flux densities. The S04 SFG model is derived from the local luminosity function of SFGs (from Sadler et al. 2002) with luminosity evolution of the form (1+z)^2.5 to z = 2 (and constant thereafter), and does not fit the source counts well by-predicting the SFG counts at the bright end and under-predicting them at the faint end. The discrepancy at the bright end may be due to the small volume probed at low-redshift where the brightest SFGs are likely to lie.

### 5 PROPERTIES OF THE RADIO STAR FORMING GALAXY POPULATION

#### 5.1 Star Formation Rates and Stellar Masses

The conversion of radio luminosity to SFR (Bell 2003) relies on the well known radio-IR relation (e.g. Yun et al. 2001). While we show in the Appendix that the radio-total IR relation does indeed hold to high redshifts/high luminosities, to derive SFRs from the radio/IR correlation in such situations requires two subtle corrections. The first is that in
determining the local correlation. \cite{Yun et al. 2001} did not apply k-corrections, which become significant for the highest luminosity galaxies in their sample. The second issue is that some of these galaxies have relatively flat radio spectra, so correcting those observed at high redshift back to 1.4 GHz using a nominal slope of −0.7 does not provide a good estimate. When nominal k-corrections are applied to the Yun et al. sample, the best fit ULIRG ratio of $L_{\text{0.4GHz}}/L_{\text{1.4GHz}}$ is $\sim 140$. We have used the observations of Condon et al. (1991) to determine a more accurate slope. We find a final ratio of $L_{\text{0.4GHz}}/L_{\text{1.4GHz}} = 128$ for a galaxy at $z \sim 2$ observed at 1.4 GHz and corrected as if it had a slope of −0.7. This result would imply that the SFRs estimated above using the standard local ratio are under-estimated by about 0.1 dex, a correction we have applied in our analysis. After these corrections and our choice of a Kroupa (2001) IMF, our conversion from radio luminosity to SFR is 0.07 dex less than that of Bell (2003), i.e. for a given radio luminosity we assume a SFR 0.84 times that predicted by Bell (2003).

We plot the SFRs of our SFG sample against redshift in Figure 4(a) using different symbols for objects of different stellar masses. Stellar mass estimates are calculated in Figure 4(a) using different symbols for objects of different stellar masses. Stellar mass estimates are calculated in Figure 4(a) using different symbols for objects of different stellar masses. Stellar mass estimates are calculated for the 13th sample of SFGs by normalising a M82 SED to our IRAC 3.6 $\mu$m fluxes (K−band for 8 sources not covered by the Spitzer data) and using a Kroupa (2001) IMF to determine a rest-frame H−band luminosities and assuming a M82 mass-to-(H−band)-light ratio. Similarly, we derived stellar masses for the 6dF-NVSS sample from their observed K−band magnitudes assuming the same M82 SED and mass-to-light-ratio. Clearly using one mass-to-light ratio for a sample of galaxies with a range of SFRs, amongst other properties, is not ideal, but this approach suffices for the current investigation. The possible selection effects of this choice are discussed in section 5.3.1.

We find two striking results. Firstly, there are many very high SFR, $> 300 M_\odot$ yr$^{-1}$, sources above $z = 1$ compared to the local Universe. The 6dF-NVSS Survey covers a large area of the sky, 17% equivalent to $\sim 7.6 \text{Gpc}^3$ to $z = 0.3$, hence is not biased against detecting rare, exceptionally high SFR sources. Therefore, the lack of exceptionally high SFR sources locally is not a volume selection effect and the presence of very high SFR galaxies at high redshift is observed in surveys at other wavelengths (e.g. in the submm Chapman et al. 2005; Muxlow et al. 2005; Pope et al. 2008). Secondly, all our high SFR galaxies have very high stellar masses. We discuss this result more within the framework of current galaxy evolution models in Section 5.3.

We can compare the SFR against stellar mass for both our sample of SFGs and the 6dF-NVSS sample in Figure 4(b) and we find that a trend of SFR correlating with stellar mass is apparent in both samples (i.e. from the local Universe up to $z \lesssim 3$). As radio flux limited surveys will always sample the highest SFR objects at any given redshift, this result is consistent with the idea that there is an upper limit to the SFR of a galaxy of a given mass. We see a similar trend in the results of Noeske et al. (2007), who find a “main sequence” relation between SFR and stellar mass at a given redshift with increasing SFR observed at higher stellar masses. The hypothesis that lower mass galaxies can only achieve lower maximum SFRs could be explained by the fact that more massive galaxies generally have more baryons in gas and dust which can act as raw material for the star formation. Potentially some of the very high radio luminosities could be over-estimated due to uncertainties in both the photometric redshift and k-correction (i.e. radio spectral index). Our radio/near-IR flux ratio cut does affect the number of sources detected with high SFR to mass ratio, at high masses/SFR/redshift. However, we have demonstrated in Section 5.3 that by varying this cut by $1 \sigma = \pm 0.12$ dex does not affect the results our AGN/SFG discrimination very much. We may have one or two AGN interlopers, but we are likely complete in a statistical sense.

5.2 Star formation history of the Universe across $0 < z < 3$

The star forming galaxies are of great interest as their radio luminosity provides a relatively unbiased measure of their star formation rate independent of the effects of dust. Using this tracer of star formation we can probe the global cos-

---

**Figure 4.** SFRs of the radio SFGs from the 13th field plotted against redshift (a) and stellar mass (b). The different symbols represent different stellar masses as indicated in panel (a). In panel (a), the solid line represents the 1.4 GHz detection limit and the dotted line indicates the 10 times $L_*$ of the radio star forming luminosity function taking a luminosity evolution of $Q = 2.5$ which we use in Section 4.3. The black dots are the star forming galaxies from the local 6dF-NVSS sample.
mic star formation rate (e.g. Lilly et al. 1996; Madau et al. 1996). We restricted the sample to all sources with \( z \leq 3 \) as we only detect two SFGs above \( z = 3 \).

The star formation rate densities are calculated using the standard \( 1/V_{\text{max}} \) method which allows for the change in detection limit across the relatively broad redshift bins. The redshift bins are chosen to be equal in size in \( \log(1+z) \) space and to have at least 50 sources per bin apart from the highest redshift bin which has 13 sources. The redshift bins are deliberately left relatively wide to mitigate large scale structure/sample variance, Poisson statistics and any possible systematic in the uncertainties of the photometric redshifts. The total star formation rate density in each redshift bin requires two corrections:

- **Radio survey incompleteness:** The radio survey is not complete down to the 30 \( \mu \)Jy detection limit at 1.4 GHz, mainly due to the attenuation of the primary beam of the VLA away from the pointing center, but also due to other instrumental effects such as band-width smearing. Hence the radio sources at low signal-noise, \( \lesssim 100 \mu \)Jy, need to be corrected by a weighting factor representing the sources not detected in our survey. The weighting factor for each source is a measure of the sky area sampled by the 1.4 GHz survey at the flux density of the source. This correction factor is a function of flux density and position away from the pointing center, i.e our detection limit is \( \sim 60 \mu \)Jy at the edge of the field. This correction is described in full in S04 and we apply the individual weightings from that work to each source.

- **Star forming radio sources below the nominal 1.4 GHz VLA detection limit:** As shown in panel (a) of Figure 4 our survey primarily probes only the high luminosity end of the SFG luminosity function, especially at high redshift. Any estimate of the star formation rate density needs to include the contribution from sources further down the luminosity function and below the detection limit. Clearly the luminosity function must evolve rapidly given the fits to the source counts (Hopkins et al. 1998; Seymour et al. 2004, etc.) and the appearance of very high SFR sources at \( z > 1 \).

The evolution of the SFG luminosity function remains slightly uncertain, but most results find a luminosity evolution of \( Q = 2 \sim 3 \), using the form \((1+z)^{5.4}\), with negligible density evolution (Rowan-Robinson et al. 1993; Seymour et al. 2004; Hopkins 2004; Huynh et al. 2003; Moss et al. 2007). Haarsma et al. (2000) use a different functional form of the evolution with more free parameters, but find quantitatively the same behaviours for luminosity and density evolution as the authors above. However, Haarsma et al. (2000) do not provide uncertainties for their fitted parameters. As there is no consensus on the evolution parameter in the literature, or the exact form of the evolution, we take a representative value of \( Q = 2.5 \pm 0.5 \), which is consistent with preliminary results from fitting the radio LF (D04), and \( P = 0 \) for the luminosity and density evolution parameters respectively. We then use the local radio SFG LF of Mauch & Sadler (2007). We use these evolution parameters to calculate the fraction of the luminosity density below our nominal detection limit for each redshift bin. We give the corresponding multiplicative correction factors and associated uncertainties in Table 5.

The uncertainties include the following effects:

- **Poisson uncertainties:** We chose the redshift bin size to include at least \( \sim 50 \) sources per bin from the highest redshift bin.

- **Uncertainty in the evolution of the Luminosity Function:** As mentioned earlier in this section, the amount of luminosity evolution of the LF remains uncertain so we have used a representative value of \( Q = 2.5 \pm 0.5 \). Hence we include this uncertainty when derived the uncertainty of the SFRD. The effect of including this factor gets stronger at higher redshifts as can be seen in Figure 5 and the LF correction factor in Table 5.

- **Sample Variance:** Sometimes referred to as Cosmic Variance, this effect is really quantifying how representative our narrow field is of the whole sky. The source counts between different fields do vary by 10 – 20% as discussed earlier, but accurately measuring the field to field variation between different surveys is tricky due to different methods used and in some cases different telescopes to correct for instrumental effects that dominate at the faint end. This issue needs to be addressed by the different teams working on deep radio surveys although we previously noted in Section 4 that several major surveys are now in reasonable agreement. Hence, to allow for sample variance we simply add a further 20% uncertainty.

We further investigate the effects of changing the two main discriminators (the two flux density ratios as described in Section 3.3). When changing both these cuts in favour of the SFGs we get an increase in the densities, but this is barely noticeable in the lowest redshift bin and increases the highest redshift bin by just 10%. When changing the cuts
the other way, in favour of the AGN, the densities decrease, but only by a few percent at the lowest redshift and by 23% in the highest redshift bin. Clearly the effect of changing the selection criteria is strongest in the highest redshift bin, but this result is not unexpected since this bin typically contains the lowest S/N radio sources and lowest number of sources. The flux ratio discriminators are least good at the highest redshifts, and the radio morphology/spectral index methods cannot be applied because most objects are too faint. Furthermore, these changes are generally smaller than the combined uncertainties from the effects listed above and hence indicate that the AGN/SFG discrimination criteria used in Section 4 are not the largest uncertainty in deriving the SFRD at the highest redshift.

The results of our determination of the comoving star formation rate density of the Universe as a function of redshift are presented in Table 5 and Figure 6. These results agree well with the multi-wavelength sample from Hopkins et al. (2004), converted to a Kroupa IMF, showing the rapid rise and fall of the contribution from the 6df sample) we can see the dramatic, fractional contribution by luminosity density in Figure 6, but note that the distribution by number density is very similar. Hence, number density and luminosity density are both good tracers of downsizing.

While the sample shown in Figure 6 represents about one quarter of the star formation occurring at a given cosmic epoch, the L1.4GHz > 10 × L∗ sources are the most active at any redshift. We find that there is a dramatic change in the stellar mass of the galaxies contributing to this part of the luminosity function. The highest redshift bin is dominated by massive galaxies, log(M/M⊙) > 11.25, although at this redshift we are not quite complete to L1.4GHz = 10 × L∗ and hence we mark points in this bin as limits. In the lowest redshift bin (from the 6df sample) we can see the dramatic, rapid rise in the number of the least massive galaxies. We are able to examine “downsizing” too with our unique radio-selected sample of star forming galaxies across z < 2. In this section we chose to look just at the contribution from the L1.4GHz > 10 × L∗ galaxies where we are mostly complete up to z = 2, Figure a). The L1.4GHz > 10 × L∗ top end of the luminosity function represents the top 28% of the total SFR density at any redshift, for the best fitting Mauch and Sadler (2007) LF assuming pure luminosity evolution. Hence we can divide each SFRD bin into the contribution by stellar mass including that of the local sample from [Mauch & Sadler (2007)]. We only show the fractional contribution by luminosity/SFR density in Figure 6, but note that the distribution by number density is very similar. Hence, number density and luminosity density are both good tracers of downsizing.

| Redshift Range | < z > | # | LF cor. | SFRD |
|----------------|-------|---|---------|------|
| 0.10 − 0.52    | 0.29  | 104 | 1.35^{+3.5\%}_{-3.8\%} | −1.48^{+0.09}_{-0.11} |
| 0.52 − 1.10    | 0.79  | 87  | 2.68^{+21.0\%}_{-20.0\%} | −1.07^{+0.12}_{-0.16} |
| 1.10 − 1.90    | 1.47  | 54  | 4.60^{+48.3\%}_{-38.1\%} | −0.83^{+0.19}_{-0.26} |
| 1.90 − 3.00    | 2.40  | 15  | 6.43^{+81.6\%}_{-53.2\%} | −0.92^{+0.27}_{-0.43} |

### 5.3 Contribution to star formation rate density by galaxy stellar mass

Recent studies of the star formation history of the Universe have not only measured the rapid change in global SFR density, but also the demographics of the star forming galaxies. Many authors have observed the evolution of the distribution of star formation moving high mass galaxies at high redshift to lower mass galaxies at lower redshifts (e.g. Cowie et al. 1996; Panter et al. 2004; Juneau et al. 2003; Panter et al. 2004; Noeske et al. 2007). This effect has been termed “downsizing” and is analogous to (and possibly related to) the apparent shift of the peak number density of AGN to lower redshifts for lower X-ray luminosities (e.g. Ueda et al. 2003).

We are able to examine “downsizing” too with our unique radio-selected sample of star forming galaxies across < z < 2. In this section we chose to look just at the contribution from the L1.4GHz > 10 × L∗ galaxies where we are mostly complete up to z = 2, Figure b). The L1.4GHz > 10 × L∗ top end of the luminosity function represents the top 28% of the total SFR density at any redshift, for the best fitting Mauch and Sadler (2007) LF assuming pure luminosity evolution. Hence we can divide each SFRD bin into the contribution by stellar mass including that of the local sample from [Mauch & Sadler (2007)]. We only show the fractional contribution by luminosity/SFR density in Figure 6, but note that the distribution by number density is very similar. Hence, number density and luminosity density are both good tracers of downsizing.

While the sample shown in Figure 6 represents about one quarter of the star formation occurring at a given cosmic epoch, the L1.4GHz > 10 × L∗ sources are the most active at any redshift. We find that there is a dramatic change in the stellar mass of the galaxies contributing to this part of the luminosity function. The highest redshift bin is dominated by massive galaxies, log(M/M⊙) > 11.25, although at this redshift we are not quite complete to L1.4GHz = 10 × L∗ and hence we mark points in this bin as limits. In the lowest redshift bin (from the 6df sample) we can see the dramatic, rapid rise in the number of the least massive galaxies. We are able to examine the rise and fall of the contribution from intermediate stellar mass ranges at successive intermediate redshift ranges.

These results are qualitatively similar to other recent results (e.g. Juneau et al. 2005; Panter et al. 2007), but are difficult to compare quantitatively as they differ in the selection details. The differences are largely due to the very different survey volumes probed and methods of determining the star formation history. Juneau et al. (2005) reach lower SFRs determined from optical emission lines from sources in Gemini Deep Deep Survey (GDDS) over an area 20 times smaller than the work presented here, hence their sample includes far fewer of the rarer, extremely high SFR objects that we find. Panter et al. 2007 use the data from the Sloan Digital Sky Survey Third Data Release (SDSS DR3 covering a far greater area than our survey, ~ 5200 deg^2) and model the galaxy spectra to determine the individual and global star formation histories.

What Figure 6 truly shows us is the fall of the contribution by massive galaxies to the global SFR density. We cannot rule out that the contribution of the least massive to
the total SFRD remains approximately constant over this redshift range. As the most massive galaxies are capable of the highest SFRs they dominate the upper end of the luminosity function at the high redshift which we explore. It is likely that as these massive galaxies are capable of such high SFRs they use up their material to form stars very quickly and hence quash their star formation rate.

5.3.1 Selection effects

We are selecting our star forming galaxies on a SFR indicator that is completely unbiased with respect to obscuration and with little selection on redshift beyond that implied by our radio flux density limit. At any redshift we are naturally detect just the most luminous, and hence highest SFR galaxies. One thing to consider is whether the apparent observed downsizing is simply an effect of missing low-mass galaxies in our high redshift bins. SFGs in our lowest mass bin only become un-detectable at \( z \geq 3 \) in our \( K \)-band or IRAC data. Low mass SFGs at these redshifts with SFRs high enough to be included in our sample would extremely high Specific SFRs (\( > 10^{-9} \text{yr}^{-1} \)) and we argue in §3.6.1 that we have are unlikely to have missed any such extreme sources. Hence, the low detection rate of low mass galaxies in the high and intermediate redshift bins is not due to our detection limits.

One might argue that the trend of fewer high stellar mass galaxies at lower redshift may be a volume selection effect. However, we can compare the number of SFGs selected from their high SFR to that expected purely on mass selection. In the lowest redshift bin for the 13\( ^{12} \)H sample, \( 0.1 \leq z \leq 0.4 \), we would expect to detect \( \sim 0.2 \) galaxies in the highest mass bin in this volume simply using the fitted Schechter function to the local stellar mass function of SFGs from Panter et al. (2007) (assuming no evolution from \( z = 0 \). Fontana et al. 2006). This prediction is consistent with our result of no galaxies found in this bin. In the highest redshift bin we would expect to detect \( \sim 40 \) high mass galaxies using the same method as before, i.e. assuming no evolution of the mass function. However, given that Fontana et al. (2006) suggest that this part of the mass function is not in place until \( z \leq 1 \) this estimate of \( \sim 45 \) may be an upper-limit and hence is consistent with our result where we detect 31 high mass galaxies in this redshift bin. These rough estimates have to be treated as such as the whole of the highest mass bin is above the knee of the stellar mass function where the space density changes most rapidly and is hardest to measure accurately. However, it is encouraging to see that number of massive galaxies varies approximately as expected. The ratio of massive to low mass galaxies must, of course, decrease toward higher redshifts if there is hierarchical evolution in the mass function, but our selection on SFR shows the opposite trend with a higher ratio of high mass to low mass galaxies at higher redshift.

A further factor to consider is the choice of a single mass-to-light ratio for the entire SFG sample. Mass-to-light ratios can vary by over an order of magnitude from active to quiescent galaxies, but most of our sample are clearly quite active by any standard, hence any variation in the ratio will be much less than this amount. Photometric stellar masses used here are also quite model dependent unlike direct dynamical measurements. There is quite a debate concerning photometric stellar masses in the literature at the moment (e.g. Maraston 2005). We note, though, that relative photometric stellar masses are more accurate than absolute photometric stellar masses so the general trends examined in this section and the next are genuine cosmological effects.

5.4 Characteristic Times

The specific star formation rate (SSFR) of a galaxy is defined as its star formation rate per unit stellar mass, and is representative of how active a galaxy is compared to its past properties. For all but the most massive galaxies our survey is biased against low SSFRs as we are selecting on SFR only. The inverse of the SSFR has been referred to as the characteruis time scale (e.g. Juneau et al. 2005). This number has units of time and gives an idea of the nature of the star formation going on in the galaxy. For example if at a given redshift the characteristic time of a galaxy is less than the age of the Universe (or the time since the galaxy formed) then the current SFR is greater than the mean historic SFR and the galaxy can be said to be in a “burst mode”. Conversely if the characteristic time is greater than the age of the Universe at a given time then the observed SFR is lower than the mean historic SFR and the galaxy can be said to be in a “quiescent” mode. In Figure 7 we plot the characteristic time as a function of redshift and along with the time since the Big Bang, \( z = 5 \) and \( z = 3 \). Most of our star forming galaxies can be classified as being in “burst mode”, although this classification becomes less certain at high redshift as it more strongly depends on the redshift of galaxy formation. This result implies that the current observed star formation rates in most of the galaxies selected here are likely due to some trigger event beyond the initial gravitational collapse and formation of the galaxy, perhaps AGN activity or galaxy-galaxy interaction. The fact that we
Figure 7. The “characteristic time” (the inverse of the SSFR) of the radio star forming galaxies plotted against redshift. The slowly decreasing solid line indicates the age of the Universe at a given redshift and the dotted (dot-dashed) line indicates the time since $z = 5$ (3). Galaxies below these lines are forming stars at a faster rate than they were in the past and are said to be in a “burst mode” and those galaxies above the line are said to be in “quiescent mode”. For reference, the Milky Way has a characteristic time scale of $\sim 100$ Gyr putting it firmly in the quiescent region of the figure (and off the plot), whilst M82 has a characteristic time of $\sim 0.7$ Gyr, well in the local burst region.

detect the most SFGs in “burst mode” is simply a function of the depth of the survey of the parent sample. All but the lowest redshift sources have SFRs $> 10 M_\odot$ yr$^{-1}$, already an elevated value for most local galaxies. A much lower radio flux density limit is necessary to detect significant numbers of “quiescent” galaxies at any kind of distance.

6 CONCLUSIONS

We present the analysis of a multi-wavelength follow up to one of the deepest radio surveys currently published. These data provide spectroscopic and photometric redshifts which are vital in discerning the nature of the sub-mJy radio population. With a philosophy of minimising the assumptions about the nature of this population we consider four discriminators between AGN and SFGs based on purely the radio, or relative radio, properties of each source. These four discriminators are: radio morphology, radio spectral index, radio/near-IR and mid-IR/radio flux density ratios. We find that 178 objects in the parent sample were classified as AGN by at least one of our AGN discriminators and $\sim 90\%$ of these are classified by at least one of the flux ratio methods methods. Our radio-selected parent sample contains a roughly 40/60 mix of AGN and SFGs, but with AGN dominating at high radio flux densities and SFGs dominating at faint flux densities. By recalculating the Euclidean normalised source counts by source type we find that the up-turn of the counts below 1 mJy is mainly due to SFGs, but still with a $\sim 25\%$ contribution from AGN at the faintest flux densities. This result is consistent with previous model fits to the source counts and estimates from ultra-deep MERLIN imaging.

We find many galaxies at high redshift which have SFRs exceeding those found in the local Universe and that these galaxies tended to be more massive than SFGs at lower redshift. We also find a trend of SFR correlating with stellar mass at all redshifts from the 6dF-NVSS sample and the 13th sample, i.e. for a galaxy at a given redshift and stellar mass there appears to be an upper-limit to the SFR possible. After correcting for radio SFGs below our nominal detection limit ($4\sigma = 30$ $\mu$Jy at 1.4 GHz), we derive the comoving star formation rate density as a function of redshift. We find our results are consistent with those derived by methods at other wavelengths. We are able to look at the population of sources in the top end of the luminosity ($L_{1.4\text{GHz}} > 10 \times L_\star$) as a function of redshift and find that the typical mass of the sources making up the top one quarter of the star forming luminosity function changes dramatically with redshift. We also find that the characteristic time of the SFGs was generally low implying an enhanced current SFR for most galaxies compared to their past mean SFR.

The Radio Morphology and Radio Spectral Index discriminator methods should be just as powerful as the flux ratio methods if deeper high resolution and multi-wavelength data were available. The mid-IR/radio flux density ratio would be improved by deeper mid-IR data. Radio luminosity, not used as a discriminator in this work, will become a powerful discriminator when larger volumes are probed in deeper and wider surveys. Unless the radio sources undetected at any other wavelength are extremely obscured (i.e. $A_V > 8$), then we are able to reject the hypothesis that they are low-mass SFGs at $z \sim 1$ because none of these radio sources have detections in our sensitive $u$, $B$, and $g'$-band imaging. Such sources are most likely high redshift ($z > 2$), obscured type-2 AGN.

These results imply that deeper future radio surveys from eVLA, eMERLIN, LOFAR and (eventually) SKA will mainly detect SFGs, not only high SFR objects at extreme redshifts, but also low luminosity, more quiescent SFGs at the redshifts probed in this work, giving a better view of the star formation in the distant Universe from radio data. The fraction of AGN is still non-negligible hence discrimination between AGN and SFGs will be the principal challenge in exploiting future surveys. This discrimination is by no means easy and, at least at present, largely statistical. Future surveys will need to be backed up by multi-wavelength data, particularly mid-IR and near-IR, photometry, to confidently separate the SFGs and AGN, as well as deeper low frequency and high resolution radio data.

ACKNOWLEDGMENTS

We thank the referee for help improving the presentation of this paper. We thank V. Smolčić, P. Capak, K. Sheth, M. Huynh and R. Norris for useful discussions. We thank T. Mauch for help with the 6dF-NVSS data set. We thank M. Jarvis for providing his model prior to publication. We thank K. Gunn much help in this project over the years. AMH acknowledges support provided by the Australian Research Council in the form of a QEII Fellowship (DP0557850). This work is based in part on data obtained with the Spitzer...
REFERENCES

Appleton P. N., et al., 2004, ApJS, 154, 147
Armus L., et al., 2007, ApJ, 656, 148
Barger A. J., Cowie L. L., Wang W.-H., 2007, ApJ, 654, 764
Bauer F. E., Alexander D. M., Brandt W. N., Schneider D. P., Treister E., Hornschemeier A. E., Garmire G. P., 2004, AJ, 128
Bell E. F., 2003, ApJ, 586, 794
Bertin E., Arnouts S., 1996, Astron. Astrophys. Suppl. Ser., 117, 393
Beswick R. J., Muxlow T. W. B., Thrall H., Richards A. M. S., Garrington S. T., 2008, MNARAS in press
Biggs A., Ivison R., 2006, MNARAS, 371, 963
Bolzonella M., Miralles J.-M., Pelló R., 2000, A&A, 363, 476
Boyle B. J., Cornwell T. J., Middelberg E., Norris R. P., Appleton P. N., Smail I., 2007, MNARAS, 376, 1182
Chapman S. C., Blain A. W., Smail I., Ivison R. J., 2005, ApJ, 622, 772
Condon J. J., 1992, ARA&A, 30, 575
Condon J. J., Huang Z.-P., Yin Q. F., Thuan T. X., 1991, ApJ, 378, 65
Cowie L. L., Songaila A., Hu E. M., Cohen J. G., 1996, AJ, 112, 839
Donley J. L., Rieke G. H., Rigby J. R., Pérez-González P. G., 2005, ApJ, 634, 169
Dunlop J. S., Peacock J. A., 1990, MNRAS, 247, 19
Elvis M., et al., 1994, ApJS, 95, 1
Fanaroff B. L., Riley J. M., 1974, MNARAS, 167, 31
Farrah D., Afonso J., Efstathiou A., Rowan-Robinson M., Fox M., Clements D., 2003, MNARAS, 343, 585
Fazio G. G., et al., 2004, Astrophys. J., Suppl. Ser., 154, 10
Fomalont E. B., Kellermann K. I., Cowie L. L., Capak P., Barger A. J., Partridge R. B., Windhorst R. A., Richards E. A., 2006, ApJS, 167, 103
Fontana A., et al., 2006, A&A, 459, 745
Garrett M. A., 2002, A&A, 384, L19
Gawiser E., et al., 2006, ApJS, 162, 1
Haarsma D. B., Partridge R. B., Windhorst R. A., Richards E. A., 2000, ApJ, 544, 641
Hopkins A. M., 2004, ApJ, 615, 209
Hopkins A. M., Afonso J., Chan B., Cram L. E., Georgakakis A., Mobasher B., 2003, AJ, 125, 465
Hopkins A. M., Mobasher B., Cram L., Rowan-Robinson M., 1998, MNARAS, 296, 839
Huynh M. T., Jackson C. A., Norris R. P., 2007, AJ, 133, 1331
Huynh M. T., Jackson C. A., Norris R. P., Prandoni I., 2005, AJ, 130, 1373
Ivison R. J., et al., 2007a, ApJL, 660, L77
Ivison R. J., et al., 2007b, MNARAS, 380, 199
Jarvis M. J., Rawlings S., 2004, New Astronomy Review, 48, 1173
Juneau S., et al., 2005, ApJL, 619, L135
Kellerman K. I., Sramek R., Schmidt M., Shaffer D. B., Green R., 1989, Astron. J., 98, 1195
Kramer I. J., Ekers R. D., Bryant J. J., Hunstead R. W., Sadler E. M., De Breuck C., 2006, MNARAS, 371, 852
Kovács A., Chapman S. C., Dowell C. D., Blain A. W., Ivison R. J., Smail I., Phillips T. G., 2006, ApJ, 650, 592
Kroupa P., 2001, MNARAS, 323, 231
Lacy M., et al., 2005, Astrophys. J., Suppl. Ser., 161, 41
Lacy M., Petric A. O., Sajina A., Canalizo G., Storrie-Lombardi L. J., Armus L., Fadda D., Marleau F. R., 2007, AJ, 133, 186
Lilly S. J., Ferrer O. L., Hammer F., Crampton D., 1996, Astrophys. J., 460, L1
Madau P., Ferguson H. C., Dickinson M. E., Giavalisco M., Steidel C. C., Fruchter A., 1996, Mon. Not. R. Astron. Soc., 283, 1388
Maraston C., 2005, MNARAS, 362, 799
Mauch T., Sadler E. M., 2007, MNARAS, 375, 931
Miller L., Peacock J. A., Mead A. R. G., 1990, MNARAS, 244, 207
Moss D., Seymour N., McHardy I. M., Dwelly T., Page M. J., Loaring N. S., 2007, MNARAS, 378
M’Hardy I. M., et al., 1998, MNARAS, 295, 641
Muxlow T. W. B., et al., 2005, MNARAS, 358, 1159
Noeske K. G., et al., 2007, ApJL, 660, L43
Panter B., Heavens A. F., Jimenez R., 2004, MNARAS, 355, 764
Panter B., Jimenez R., Heavens A. F., Charlot S., 2007, MNARAS, 378, 1550
Papovich C., et al., 2007, ArXiv e-prints, 706
Pope A., et al., 2006, MNARAS, 370, 1185
Richards E. A., 2000, Astrophys. J., 533, 611
Rieke G. H., et al., 2004, Astrophys. J., Suppl. Ser., 154, 25
Rowan-Robinson M., Benn C. R., Lawrence A., McMahon R. G., Broadhurst T. J., 1993, MNARAS, 263, 123
Sadler E. M., et al., 2002, MNARAS, 329, 227
Saunders W., Rowan-Robinson M., Lawrence A., Efstathiou G., Kaiser N., Ellis R. S., Frenk C. S., 1990, MNARAS, 242, 318
Sajina, A., Yáñez, L., Lacy, M., & Huynh, M. 2007, ApJL, 667, L17
Schinnerer E., et al., 2007, ArXiv Astrophysics e-prints, 172, 46
Seymour N., 2002, PhD thesis, University of Southampton, UK
Seymour N., McHardy I. M., Gunn K. F., 2004, MNARAS, 352, 131
Simpson C., et al., 2006, MNARAS, 372, 741
Spergel D., et al., 2003, Astrophys. J., Suppl. Ser., 148, 175
Stern D., et al., 2005, ApJ, 631, 163
Stern D., Spinrad H., 1999, Publ. Astron. Soc. Pac., 111, 1475
Thompson T. A., Quataert E., Waxman E., Murray N., Martin C. L., 2006, ApJ, 645, 186
Ueda Y., Akiyama M., Ohta K., Miyaji T., 2003, ApJ, 598, 886
Vlahakis C., Eales S., Dunne L., 2007, MNARAS, p. 605
Werner M. W., et al., 2004, Astrophys. J., Suppl. Ser., 154, 261
...
APPENDIX A: REDSHIFT DEPENDENCE OF THE RADIO-IR RELATION

The radio-IR relation refers to the very close correlation, over five orders of magnitude, of the radio and IR luminosities of star forming galaxies (Condon et al. 1991; Yun & Carilli 2002) as the radio and IR luminosities are directly related to star formation. To use radio data as a measure of star formation, we need to determine if the radio-IR relation, from which radio/SFR calibrations are ultimately derived, holds or changes above $z = 1$ (it has been shown to hold up to $z \sim 1$ in the mid-IR, Appleton et al. 2004). In fact, two recent studies have indicated that a change is possible (Kovács et al. 2006; Vlahakis et al. 2007). We proceeded somewhat differently from these studies to avoid two possible sources of bias. Firstly, we take a sample of radio-selected, high redshift galaxies (which have ULIRG or near-ULIRG luminosity) and a sample of local ULIRGs only, since the relation has not shown to be luminosity-independent into the ULIRG range (i.e. local samples from Yun et al. 2001 and Bell 2003 are restricted to sub-ULIRG sources, $\log(L_{\text{1.4 GHz}}/\text{WHz}^{-1}) \leq 24$). Secondly, we compared the radio and IR rest-frame wavelength fluxes between the local ULIRGs and high redshift galaxies, since free-free absorption can flatten the radio spectrum and make extrapolations back to rest-frame 1.4 GHz uncertain.

First, we assembled a local comparison sample of ULIRGs dominated by star formation (according to the studies of Farrah et al. 2003; Armus et al. 2007) and with radio measurements at least at 1.4 and 8.4 GHz (Condon et al. 1991). There are seven galaxies that meet these requirements; Arp 220, IRAS 1056, IRAS 1211, IRAS 1434, IRAS 1525, IRAS 17208 and IRAS 2249. Figure A1 shows their spectral energy distributions, normalized at 260 $\mu$m. We over-plotted the measurements of Kovács et al. (2006) of high redshift galaxies at 1.4 GHz and 350 and 850 $\mu$m. We have not shown the measurements of galaxies at $z < 1.4$, and we also rejected measurements of three systems that are likely to be influenced by AGN and one more not detected at 350 $\mu$m: numbers 2, 3, 9, and 10 in their Table 1. Where they were available, we used the improved 1.4 GHz radio flux densities measurements from Biggs & Ivison (2006) instead of those from Kovacs et al. (2006).

We normalised the plotted points to provide a good fit at both 350 and 850 $\mu$m (observed) to the SEDs of local ULIRGs. As Figure 1 shows, the radio and IR flux densities indicated for the high redshift galaxies (1.4 $\leq z \leq 3.4$) agree well with the envelope of the SEDs of the local ULIRGs. In the radio, there is no apparent offset from the local galaxies, but the scatter is considerably larger than for the local ULIRGs. However, a significant part of this larger scatter is likely due to measurement errors, since many of the 1.4 GHz flux densities have relatively low signal to noise. A further explanation for the scatter is that the high redshift starbursts have a wider range of radio spectral indices.

This paper has been typeset from a TeX/LaTeX file prepared by the author.
This figure "figure1.gif" is available in "gif" format from:

http://arXiv.org/ps/0802.4105v1