PROCEEDINGS OF SCIENCE

Categorising the sub-mJy population: Star-forming galaxies from deep radio surveys

Tom Dwelly[*a], **Nick Seymour**[b], **Ian M**[c]**Hardy**[a], **Derek Moss**[a], **Abdu Zhogbi**[a], **Mathew Page**[c], **Andrew Hopkins**[d], **George Rieke**[e], **Nicola Loaring**[f]
[a]*School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK*
[b]*Spitzer Science Centre, Caltech, 1200 East California Boulevard, Pasadena, CA 91125, USA*
[c]*Mullard Space Science Laboratory, UCL, Holmbury St. Mary, Surrey, RH5 6NT, UK.*
[d]*School of Physics, University of Sydney, Sydney, Australia*
[e]*Steward Observatory, University of Arizona, Tuscon, Arizona, USA*
[f]*SALT, PO box 9, Observatory, 7925, South Africa*
E-mail: `td@phys.soton.ac.uk`, `seymour@ipac.caltech.edu`

Models predict that starforming galaxies make up the majority of the source population detected in the very deepest radio surveys. Radio selected samples of starforming galaxies are therefore a potentially excellent method to chart e.g. the cosmic history of star-formation. However, a significant minority of the faintest radio sources are AGN powered 'contaminants', and must be removed from any solely star-formation powered sample. Here we descibe a multi-pronged method for spearating star-forming and AGN powered sources in a deep 1.4 GHz radio survey. We utilise a wealth of multi-wavelength information, including radio spectral and morphological information and radio to mid-IR SED modelling, to select a clean sample of star-formation powered sources. We then derive the 1.4 GHz source counts separately for AGN and SFGs, calculate an independent measure of the evolving star-formation rate density to z$\sim$2, and compare our results to the star-formation rate density determined at other wavelengths.

From planets to dark energy: the modern radio universe
October 1-5 2007
University of Manchester, Manchester, UK

*Speaker.

PoS(MRU)051

1. Introduction

There is now good agreement between the various methods of estimating the space density of star-formation rate (SFRD) at low redshifts ($z < 1$), with uncertainties around 30–50%. However, the situation at higher redshifts remains much less clear, with uncertainties in the SFRD, due to e.g. poorly known dust absorption corrections, of as much as 300–500% [1]. Radio emission from star-forming galaxies (SFGs) is unaffected by absorption and scales roughly linearly with star-formation rate [2], thus the radio luminosity of SFGs provides an excellent independent unbiased measure of their star-formation rate. The current deepest ‘blank field’ radio surveys (reaching $<10\,\mu$Jy rms at 1.4 GHz) are sensitive enough to detect starburst galaxies out to z$\sim$2, and so potentially offer an excellent way to measure the SFRD. However, a significant fraction of the faint radio population are AGN ’contaminants’, which must be filtered out in order to get a sample of purely starburst powered radio sources. In the past, various strategies have been adopted to carry out this SFG/AGN separation. For example in the local sample of [3], optical emission lines were used to identify the presence of AGN in the host galaxies of bright radio selected sources. However, due mainly to their typical faintness at optical wavelengths, such techniques are not feasible for sub-mJy radio sources, and the nature of the very faint radio population remains unknown (e.g.[4],[5]). Now is a very opportune time to consider this problem with the imminent massive increase in radio survey sensitivity (LOFAR, eMERLIN, e-VLA, SKA etc), which will deliver massive samples of very faint radio sources.

2. Separating starbursts from AGN in deep radio surveys

Below 1 mJy the 1.4 GHz Euclidean normalised source counts show a strong upturn above that expected from an extrapolation of the counts from higher flux densities; it is suggested that the bulk of this upturn is due to starforming galaxies. The source counts at 1.4 GHz (and at 610 MHz) can be reasonably well modeled by an AGN population (dominant at high fluxes), and a starforming population that evolves rapidly with redshift (dominant below a few 100 μJy, [4],[6]) However, due mainly to the typical faintness of the radio sources at shorter wavelengths, it has not yet been possible to determine directly the fractional contributions from SFGs and AGN to the source counts as a function of flux density.

We present results here from our multi-wavelength survey of the ‘13^H deep field’ (lying at $13^H34^m, +37^\circ54'$), a high Galactic latitude field that has been targeted with deep observations from X-rays to radio. Our starting point is the sample of radio sources detected in the 1.4 GHz VLA A+B array maps (which reach to 7.5μJy rms with $\sim$3” resolution, and cover a 30’ diameter region), as reported in [4]. These 449 sources constitute the ‘parent sample’ discussed here. We have used a number of techniques to determine the most likely radio power source for the objects in this parent sample. We prefer to use only AGN/SFG discrimination techniques that are dependent on the radio emission itself. This is important because some radio sources may contain an AGN, but may have their radio emission powered mainly by star-formation. Therefore, to work out the power sources for the sub-mJy sources, radio-related diagnostics are the most direct. For each radio source we look for any sign that it is AGN powered in the following diagnostics: radio morphology and spectral indices, absolute radio luminosity, radio to 24μm flux density ratio, and radio to K-band flux density ratio. Any sources that show no sign of being an AGN in every one of these diagnostics are most likely powered by star-formation.

We have obtained 163 spectroscopic redshifts for radio sources in the 13^H field with multi-object spectrographs on the WHT, CFHT and Keck telescopes. This spectroscopic redshift information is supplemented with photometric redshifts calculated using our deep ground based optical/near-IR, and *Spitzer-IRAC* imaging in the u^*,B,g',R,i',I,z',Z,J,H,K,3.6,4.5, and 5.8μm bands (Dwelly et al., in prep). We have tested the accuracy of the photometric redshifts by comparison with the spectroscopic values, and find a scatter of ~ 0.05 in $\Delta z/(1+z)$ for galaxies not spectroscopically classed as broad emission line AGN. Star-formation rates are derived from the 1.4 GHz radio luminosities using the conversion from [2], which is linear for $L_{1.4GHz} > 10^{22}$ W Hz^{-1}. We assume that all sources with radio luminosities greater than $10^{24.8}$ W Hz^{-1} (equivalent to SFR$>$ 3000 $M_\odot$ yr^{-1}) must be AGN powered.

2.1 Radio morphologies and spectra

At sub-mJy levels, the best current radio morphological information comes from the MERLIN array, which has a resolution of $0.2''$ at 1.4 GHz (or about $0.5''$ if one combines VLA and MERLIN data to improve sensitivity). In the 13^H field, 18 days of MERLIN observations at 1.4 GHz are spread over four pointings, covering a 20'$\times$20' field, when combined with the VLA A-array data, these observations reach to $\sim 12\mu$Jy rms per 0.5" beam (Zhogbi et al., in prep.). Radio spectral information requires deep surveys at more than one wavelength. In the 13^H field spectral information is currently provided by a mosaic of VLA observations at 5 GHz which are sufficient to put useful constraints on the radio spectra of the brighter 1.4 GHz sources. Very recently we have also carried out over 60 hours of 610 MHz GMRT observations of the 13^H field, which will reach below 15μJy rms (e.g. [7]), and provide spectral index measurements for virtually the entire 1.4 GHz sample. All unresolved, flat spectrum radio sources (with or without linearly extended jet- or lobe-like features), are most likely AGN powered, whereas steep spectrum radio sources, resolved on roughly the scale size of their optical host galaxies, are most likely star-formation powered.

2.2 Radio/mid-IR and Radio/near-IR flux ratio diagnostics

In SFGs, the radio flux is tightly correlated with the IR emission (e.g. [8], because both trace the same star-formation processes: the high mass stars, whose dust-reprocessed UV emission is seen in the IR, are the same objects that become supernovae and generate the synchrotron emission seen in the radio. The 13^H field is covered by deep *Spitzer-MIPS* imaging of comparable sensitivity to the 1.4 GHz data. We use the 24μm/1.4 GHz flux density ratio as a AGN/starburst discriminator. In Fig. 1 we show the distribution of 24μm/1.4 GHz flux density for our parent sample and compare it to the tracks (as a function of redshift) expected for luminous starburst galaxy templates (Rieke et al., in prep). Any radio sources that lie far from these tracks are likely to be primarily AGN powered.

A high radio to near-IR flux ratio is expected for radio loud AGN. For starbursts, the 1.4 GHz/K-band flux density ratio is somewhat dependent on specific SFR, but always lower than for radio loud AGN. We identify as AGN all the radio sources in our sample that have significantly higher radio/K-band flux density ratios than expected for model SFG templates.

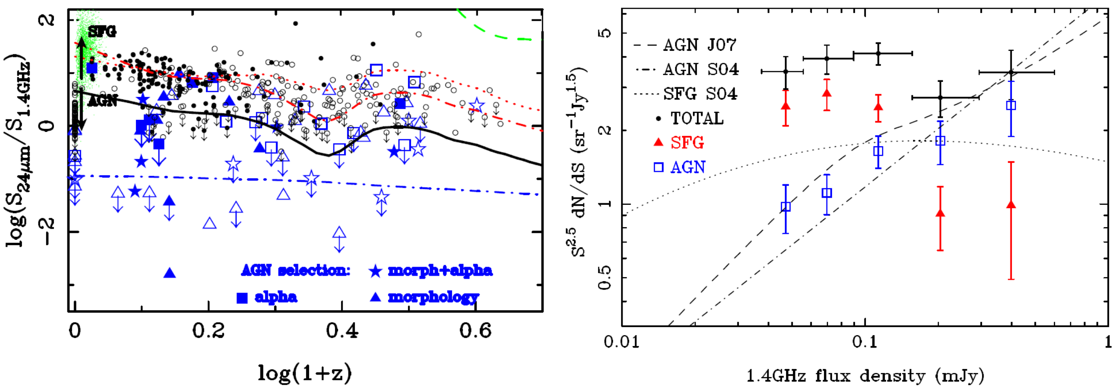

Figure 1: *Left panel:* The 24μm/1.4 GHz flux density ratios for our radio sample (points) compared to tracks expected for starburst galaxies (red lines), a radio loud AGN (blue line) and a radio quiet AGN (green line). All sources below the solid black line are inconsistent with being powered by starformation. *Right panel:* The Euclidean normalised differential 1.4 GHz source counts in the 13^H field subdivided by source type (AGN in blue, SFGs in red, and total source counts in black). We also show the source counts predicted by the model AGN and SFG populations from [4] (dot-dashed and dotted lines), and the AGN population model from Jarvis et al. (in prep, dashed lines).

3. Results

After applying the AGN/SFG discrimination techniques listed in section 2, we find that more than half (269/449) of the 1.4 GHz sources in our parent sample are most likely powered by starformation rather than accretion processes. We have useful redshift information (spectroscopic or photometric) for all of these SFG candidates.

We can now sub-divide the AGN and star forming galaxy contributions to the sub-mJy bump. Figure 1 shows the source counts below 2 mJy, with the AGN and SFGs plotted separately. We see that as predicted, the SFGs are the dominant constituent of the radio population below 1.4 GHz flux densities of $\sim 200\mu$Jy. Interestingly, the AGN population appears to be higher than the extrapolation from higher fluxes, and is very well matched by the AGN population model of Jarvis et al. (in prep), which includes a contribution from radio quiet AGN. At the faint flux limit of our survey, the SFGs constitute $\sim 2/3$ of the population, with AGN making up the remainder.

We can use the radio selected SFG sample to calculate the cosmic star-formation rate density (SFRD) as a function of redshift. In the left panel of Fig 2 we compare the measured integrated SFRD to that predicted by [1] model luminosity function. It is clear that our radio data provide a strong constraint on the SFRD. In the right panel of Fig 2 we show the total star formation history derived from our radio-selected sample of SFGs. We have used the *shape* of the SFG luminosity function [1] to correct for objects below the luminosity sensitivity limit of our data set. Our measurements of the SFRD clearly agree well with measures obtained at other wavelengths (e.g. UV, Hα, far-IR).

4. Summary and Conclusions

We have used a multi-pronged method to separate AGN and SFG powered radio sources in a deep 1.4 GHz survey of the 13^H survey field. We find that no single one of our AGN/SFG

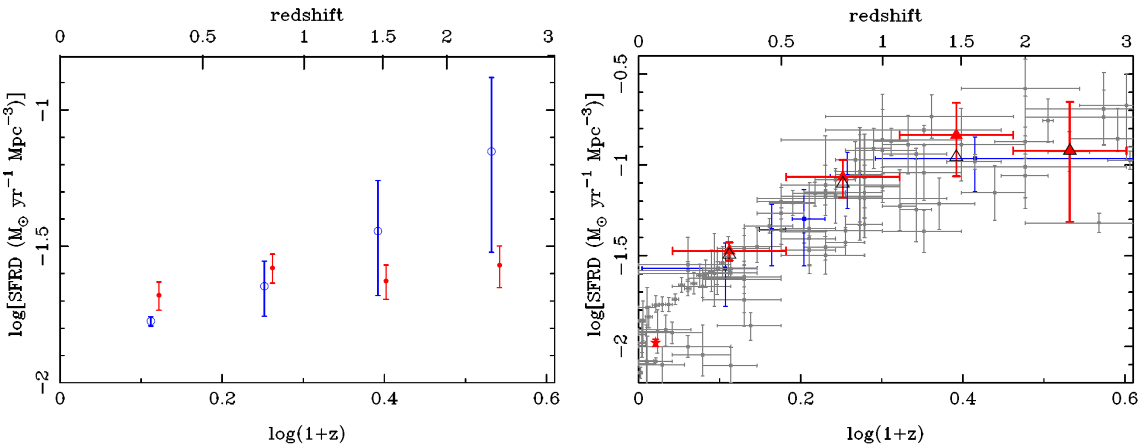

Figure 2: *Left panel:* The summed SFRD as a function of redshift for our radio-selected SFGs (red symbols). For comparison we show (in blue) the range of integrated SFRD values that are consistent with the best fitting luminosity function/evolution model of [1], where the model is integrated down to the luminosity limit of our survey. The lowest SFRs detectable (derived from the 1.4 GHz flux density limit) at the centre of each bin are approximately 3, 15, 30 and 200 $M_{\odot}$ yr^{-1} in the 0.1–0.52, 0.52–1.1, 1.1–1.9, and 1.9–3.0 redshift ranges respectively. *Right panel:* The SFRD measured in the 13^{H} field (red symbols) after correction for sources below our radio flux density limit. For comparison we show in blue the radio-based determination from [9], and in grey we show the compilation of multi-wavelength SFRD measurements taken from [1].

discrimination techniques, based on sub-arcsec radio morphological information, radio spectra, 24μm/1.4 GHz flux ratios and K-band/1.4 GHz flux ratios, is sufficient on its own. However, using a combination of all these methods one can identify a clean, flux limited sample of SFGs. We find that star forming galaxies are the major contributor below 200 μJy, and that there is some evidence for an ‘extra’ population of radio-quiet AGN. We have used the radio selected SFG sample to calculate the SFRD, and find that the radio measures are consistent with those seen at shorter wavelengths. These results will be presented more fully in Seymour et al. (submitted to MNRAS).

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