

The properties of the very weak radio source population in the GOODS/ACS HDF-N region

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Deep combination radio observations at 1.4GHz with the VLA and MERLIN have imaged a region 10 arcminutes square surrounding the Hubble Deep Field North (HDF-N). Initial studies of the weak radio source population have shown that the proportion of starburst systems increases with decreasing radio flux density with more than 70% of radio sources being starburst in nature at flux densities less than $S_{1.4 \text{ GHz}} \sim 70 \mu\text{Jy}$. More recent statistical studies of the very weak radio source population ($S_{1.4 \text{ GHz}} < 40 \mu\text{Jy}$) in an 8.5 arcminute square field centred on the HDF-N overlap the recently published GOODS ACS field. Radio emission at the level of a few μJy are statistically detected associated with ACS galaxies brighter than a z-band magnitude of 25. These very faint radio sources are interpreted as extended starburst systems with average radii in the range 0.6 to 0.8 arcseconds. Typical radio luminosities for those with measured redshifts are found to be several times that of the nearby well-studied starburst galaxy M82.

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1. Introduction

Deep galaxy studies at visible and infra-red wavelengths have indicated that early galaxies merge to form larger systems in a 'bottom-up' scenario of galaxy assembly. This implies that galaxy-galaxy interactions were common at early epochs. Such interactions at modest redshifts are seen to trigger major star-formation activity and it is well established that star-formation rate density increases dramatically out to redshifts of ~ 1 [1]. The star-formation rate for such galaxies can be estimated from both the centimetric radio and far infra-red (FIR) luminosities which have been found to be tightly correlated over several orders of magnitude [2], [3].

Differential radio source counts at 1.4GHz (See Figure 1) show an increase at flux densities below 1mJy [4]. Multi-wavelength studies of a number of fields including deep radio observations involving the VLA, ATCA, MERLIN, and the EVN, have shown that this new weak radio source population is associated with distant star-forming galaxies

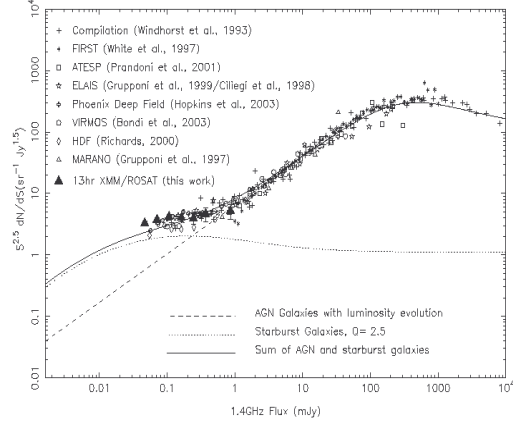


Figure 1: Normalised differential radio source counts at 1.4GHz. At flux densities below 1mJy there is an upturn which is identified with a new population of distant star-forming galaxies. [After Seymour, McHardy & Gunn (2004)]

2. The Initial Radio Study of the HDF-N

During 1996 and 1997, deep radio observations of the HDF-N region were made with the VLA and MERLIN. The VLA results were presented in [5] and [6], and the combination high angular resolution results were presented in [7]. Within a 10 arcminute square field centred on the HDF, 92 radio sources were detected by the VLA at 1.4GHz above a completeness limit of $40\mu\text{Jy}/\text{beam}$ (5.3σ) using a 2 arcsecond beam. Combination high-resolution MERLIN+VLA images involving 42 hours of VLA observations and 18 days of MERLIN data were made for small regions around each of the 92 detected sources. The rms noise level in the combination images was $\sim 3.3\mu\text{Jy}$ per 0.2 arcsecond beam making these images some of the most sensitive yet produced at 1.4GHz.

The full results of the study of the individual radio sources in the 10 arcminute field surrounding the HDF-N are given in [7] and are summarized below:

- Within the 10x10 arcminute field there are 92 radio sources with flux densities at 1.4GHz $>40\mu\text{Jy}$.
- The radio sources have angular sizes in the range 0.2 to 3 arcseconds.

- 85% of the radio sources are associated with galaxies brighter than 25th magnitude in the v-band.
- The remaining 15% are optically faint or extremely red objects lying at high redshift, some of which are detected at sub-mm wavebands.
- The radio sources can be characterized as AGN or starburst according to their radio structures with starburst systems being identified as those with steep radio spectral indices and radio structures extended on (sub-)galactic scales overlaying the central region of the optical galaxy.
- Below 60 μ Jy the radio sources are dominated by starburst type systems.
- The starburst systems typically have radio luminosities significantly greater than that of nearby well-studied starbursts such as M82 or Arp220.
- Some high redshift starburst systems show evidence for embedded AGN {garrett01}.

3. The New Study of the Very Weak Radio source Population

The initial investigation has been extended to include a statistical study of the very weak radio source population in the HDF-N region utilizing ancillary data obtained from the large multi-wavelength Great Observatories Origins Survey (GOODS). The GOODS North region partially overlies the original field, and a new wide-field contiguous combination radio image was made covering a complete 8.5 arcminute square field centred on the HDF-N which contains the region of overlap. The 8.5 arcminute square radio image covers a region of the GOODS-N field containing 13030 galaxies brighter than magnitude 28.3 in the z-band ACS catalogue.

3.1 Faint Radio Emission from Optically-selected Galaxies

The radio and optical fields are astrometrically aligned to better than 50mas. Thus the radio flux density from each of the 13030 z-band optical galaxies can be investigated by integrating the radio emission from the MERLIN+VLA image of the 8.5 arcminute square field within a radius of 0.75 arcseconds at the position of every galaxy. Radio sources brighter than 40 μ Jy have already been reported in detail in [7] and were excluded from the sample. In addition, all galaxies with nearest neighbours closer than 1.5 arcseconds were also excluded so as to avoid confusion

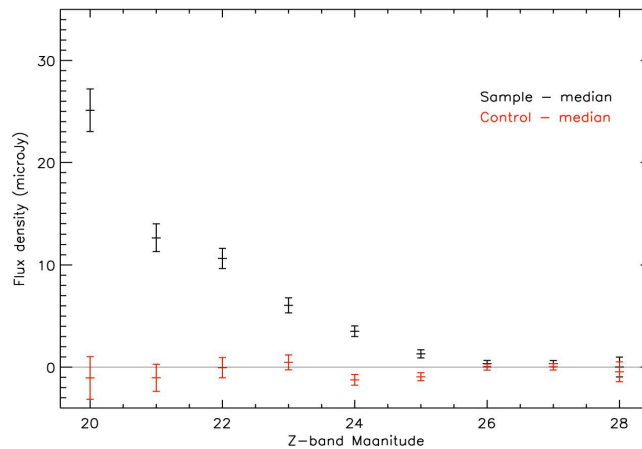


Figure 2: Median 1.4GHz flux density detected within 0.75 arcseconds of the position of optical galaxies in the ACS HDF-N field, binned by z-band magnitude. The control sample incorporates a random 7 arcsecond shift.

problems. The median flux densities, binned by z-band magnitude are shown in Figure 2. A control sample was also constructed which incorporated a random 7 arcseconds positional shift between the optical galaxy and the position searched in the radio image.

Radio emission is clearly detected statistically for all z-band magnitude bins brighter than 26. Of the ~2700 galaxies brighter than z=24mag, half (nearly 1400) will have radio flux densities of ~4μJy or greater at 1.4GHz. A 4μJy source represents an ~8σ detection for a future deep e-MERLIN+EVLA image; such galaxies which at present may only be investigated statistically will in the near future be imaged individually.

3.2 Radio Source Sizes

The angular sizes of the very weak radio sources can also be investigated statistically. In each magnitude bin the average radio source size can be derived from the radio flux densities found in annuli of width 0.25 arcseconds, over radii of 0.25 to 2 arcseconds centred on each

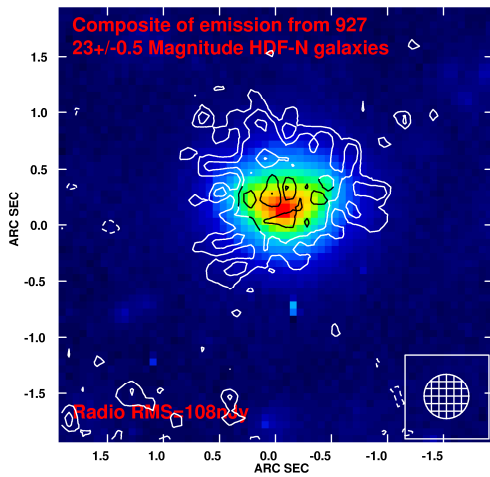


Figure 4: Composite image of the radio emission from 927 23rd mag z-band galaxies shown contoured over-laid on a false colour stacked optical image. The rms noise of 108nJy/beam in the composite radio image is close to the predicted statistical level for an average of 927 individual maps.

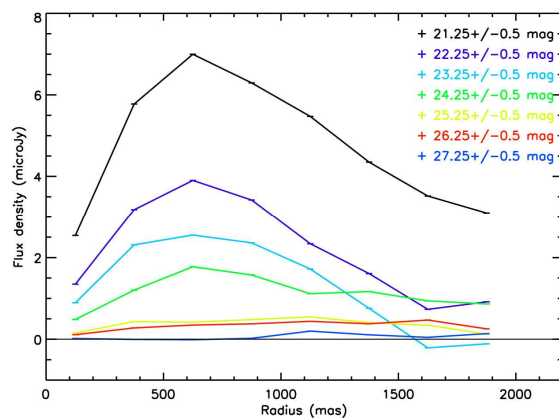


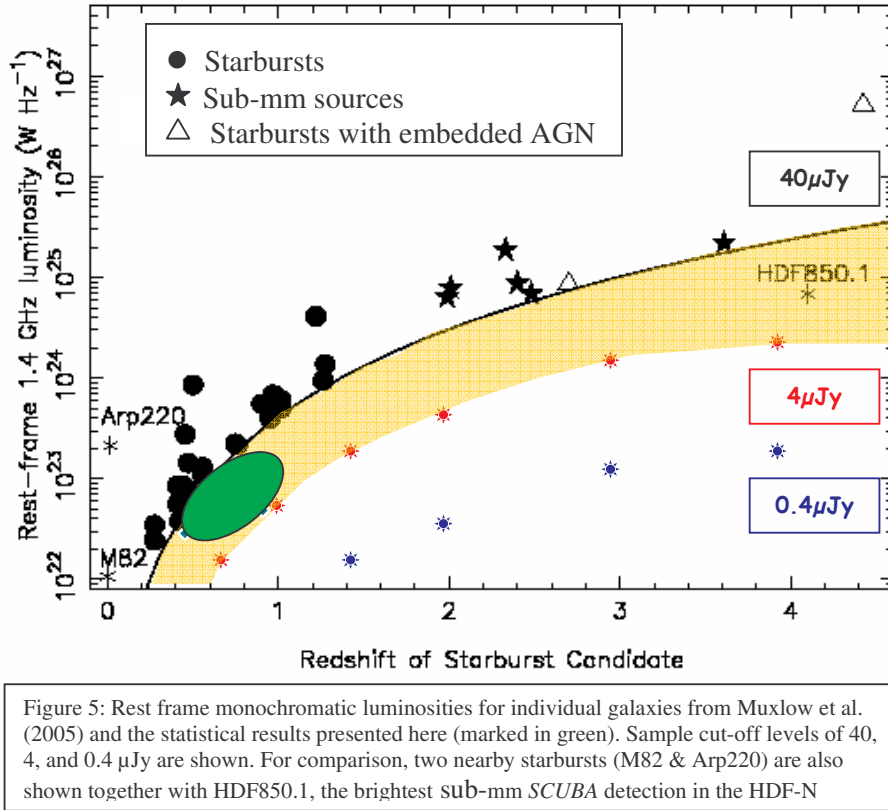
Figure 3: The average radio flux density contained within annuli of width 0.25 arcseconds over radii of 0.25 to 2 arcseconds centred at the position on each galaxy binned by z-band magnitude.

galaxy position – see Figure 3. For detected systems brighter than z~25mag, the average radio source radii are in the range 0.6 to 0.8 arcseconds implying that the next generation radio interferometers will need sub-arcsecond angular resolution. There is a marginal trend for the fainter radio sources to be slightly smaller. Radio source sizes may also be measured by fitting to the composite, stacked radio image in each magnitude bin. These are shown in Figure 4. Similar sizes are derived by this latter method.

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3.3 Starburst Luminosities

Around 1000 of the ~13000 galaxies in the 8.5 arcminute field have published spectroscopic redshifts. We have constructed the luminosity-redshift distribution for those starburst systems with measured redshifts. For this sub-set of starbursts, the detected radio flux density stacked by z-band magnitude does not differ significantly from the complete galaxy sample (at least for those bins brighter than 24th mag); indicating that the sub-set of galaxies with measured redshifts do not appear to differ significantly from the complete galaxy set. We are thus able to derive the averaged luminosity distribution for those starburst galaxies brighter than 24th mag.



The very weak radio sources which are assumed to be dominated by starbursts have average properties which indicate that they are an extension of the weaker end of the distribution of starbursts detected as individual sources at higher radio flux densities. Their typical luminosities are still several times that of M82. However, it should be noted that these weak radio sources have been selected by optical z-band properties and will therefore exclude optically faint systems. Most of the individual high redshift sub-mm starburst systems imaged by [7] were optically faint, and therefore will not be represented statistically in these results. Furthermore close galaxy pairs have also been excluded. Clearly individual imaging of these very faint systems will be required.

4 Starformation History

Using the high-resolution radio results from this study of the GOODS HDF-N region, selecting starburst sources from [7] together with an additional weak radio source sample from [8], radio counterparts to Spitzer sources from [9], and the known sub-mm sources with radio detections, it is possible to compile a sample of 300 radio sources with radio detections ($>3\sigma$ ($10\mu\text{Jy}$)) and measured redshifts. From this we have derived a plot of the star-formation rate against redshift – see Figure 6.

Our results can be compared directly with those of [10] which are derived from VLA observations of HDF, SSA13 (15 sources) and V15 (33 sources)

fields. Their sample consisted of 37 sources ($S_{1.4\text{GHz}} > 22\mu\text{Jy}$). Our results are consistent with Haarsma et al 2000 and may show evidence for a turn-over beyond a redshift of 2. However our sample is significantly incomplete and many more weak radio sources need to be investigated, especially at the higher redshifts. This will be exciting new work for *e*-MERLIN, EVLA, *e*-VLBI – and ultimately SKA.

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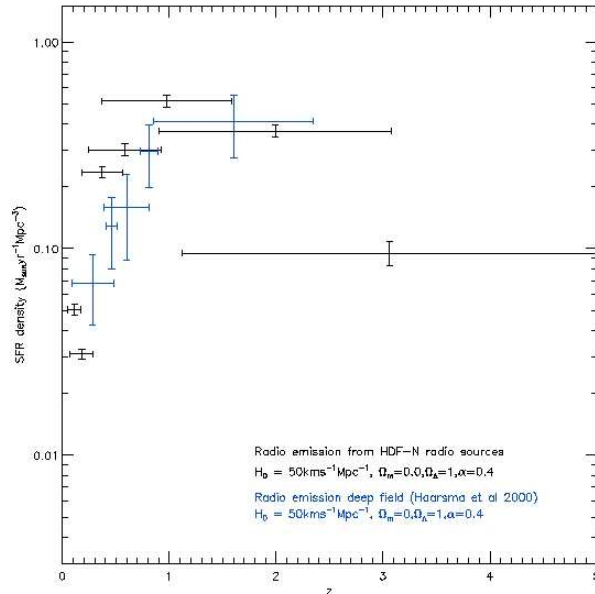


Figure6: A plot of starformation rate against redshift for our sample of 300 starforming galaxies. The results from Haarsma et al (2000) are overlaid in blue.