VLA survey of the CDFS: the nature of faint radio sources

P. Tozzi
INAF, Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I-34143 Trieste, Italy

K. Kellermann, E. Fomalont
NRAO, 520 Edgemont Road, Charlottesville, VA 22903–2475, U.S.A.

N. Miller, C. Norman
Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA

V. Mainieri, P. Padovani, P. Rosati
ESO, Karl-Schwarzschild-Strasse 2, D-85748

and the VLA–CDFS team

Abstract. We present the multiwavelength properties of 266 cataloged radio sources identified with 20 and 6 cm VLA deep observations of the CDFS at a flux density limit of 42 $\mu$Jy at the field centre at 1.4 GHz. These new observations probe the faint end of both the star formation and radio galaxy/AGN population. X–ray data, including upper limits, turn out to be a key factor in establishing the nature of faint radio sources. We find that, while the well–known flattening of the radio number counts below 1 mJy is mostly due to star forming galaxies, these sources and AGN make up an approximately equal fraction of the sub–millijansky sky, contrary to some previous results. We have also uncovered a population of distant AGN systematically missing from many previous studies of sub–millijansky radio source identifications. The AGN include radio galaxies, mostly of the low–power, Fanaroff–Riley I type, and a significant radio–quiet component, which amounts to approximately one fifth of the total sample. We also find that radio detected, X–ray AGN are not more heavily obscured than the X–ray detected AGN. This argues against the use of radio surveys as an efficient way to search for the missing population of strongly absorbed AGN.

1. Introduction

Deep multiwavelength surveys help to reconstruct the cosmic evolution of AGN and star formation processes. In this respect, X–ray and radio emission are good tracers of both processes. The radio properties of the X–ray population found in deep surveys have been studied only in a few papers based on VLA data in the Chandra Deep Field North (CDFN; Richards et al. 1998; Richards 2000; Bauer et al. 2002; Barger et al. 2007), combined MERLIN and VLA data in the CDFN region (Muxlow et al. 2005), and ATCA data in the Chandra Deep Field South (CDFS; Afonso et al. 2006; Rovilos et al. 2007). Deep radio surveys are
also realized in shallower but wider X–ray fields like COSMOS (see Schinnerer et al. 2007; Smolcic et al. 2008; 2009).

In this work, we use the deep radio data obtained with the VLA in the CDFS and Extended Chandra Deep Field South (E-CDFS) fields. The radio catalog (presented in Kellermann et al. 2008, hereafter Paper I) includes 266 sources and constitutes one of the largest and most complete samples of \( \mu \text{Jy} \) sources in terms of redshift information. Our multiwavelength approach exploits the X–ray data (see Giacconi et al. 2002; Alexander et al. 2003; Lehmer et al. 2005) and allows us to characterize both processes over a wide range of redshifts. Optical and near–IR properties of the radio sources are discussed by Mainieri et al. (2008, hereafter Paper II), a detailed analysis of the X–ray properties of radio sources is presented in Tozzi et al. 2009 (hereafter Paper III), while a multiwavelength approach to studying the source population is presented by Padovani et al. (2009, Paper IV). Here we briefly discuss the most relevant outcomes presented in this series of papers.

2. The data set

Of 266 cataloged radio sources, 89 radio sources in our complete radio catalog were found to have X–ray counterparts in either the 1 Megasecond Chandra catalog or in the E-CDFS. Using the available imaging in \( \text{i, R, K}_S, 3.6 \mu\text{m}, 4.5 \mu\text{m}, 5.8 \mu\text{m}, 8.5 \mu\text{m}, 24 \mu\text{m} \) and \( 70 \mu\text{m} \) bands from ESO/WFI, VLT/ISAAC, HST/ACS and Spitzer, we were able to find a reliable optical or infrared counterpart for 254 (\( \sim \) 95\%) radio sources. Three radio sources have no apparent counterpart at any other wavelength. We also have optical morphological classifications for \( \sim \) 61\% of the sample.

Using literature data and our own follow–up, a total of 186 (\( \sim \) 70\%) sources have a redshift: 108 are spectroscopic redshifts and 78 reliable photometric redshifts. The redshift distribution of the VLA sources peaks around \( z \approx 0.8 \) (see Figure 1, left panel). The radio sources are good tracers of large scale structures already detected at other wavebands in this region of the sky (NIR, optical, X–ray). In particular, the main peaks of our redshifts distribution are at \( z= 0.735 \pm 0.004 \) (10 objects) and \( z= 1.614 \pm 0.011 \) (6 objects), two well known overdensities in the CDFS (Gilli et al. 2003).

3. Multiwavelength Classification of sub–mJy radio sources

By analyzing the ratio of radio to optical luminosity and the radio and X–ray powers of the sources with morphological and redshift information, we have selected candidate star–forming galaxies and AGN. As the first two parameters by themselves are not very good discriminants between star–forming galaxies and AGN, optical morphology and especially X–ray data turned out to be vital in establishing the nature of faint radio sources.

In Figure 1, right panel, we show the distribution of the Sersic index (see Sersic 1968) values for radio sources in three equally populated flux density bins (see Paper II). While the properties of the host galaxies in the two brighter flux density bins look similar, we find evidences for a change in the dominant radio population at \( S \approx 0.08 \) mJy. The radio sources in the intermediate and
Figure 1. Left panel: the fractional distribution of the 186 radio sources with redshift. Dashed vertical lines mark three overdensities already identified in the X-ray sources distribution (Gilli et al. 2003). Right panel: distribution of the Sersic index values for radio sources with $S(1.4 \text{ GHz}) > 0.2$ mJy (continuous line), $0.08 < S(1.4 \text{ GHz}) < 0.2$ (hatched histogram) and $S(1.4 \text{ GHz}) < 0.08$ mJy (grey shaded histogram). The vertical line mark the value $n = 2.5$, empirical dividing value between early and late type galaxies.

Bright flux density bins show a Sersic indexes distribution that resembles that of early–type galaxies with a tail of disk dominated galaxies and in a rest–frame color–magnitude diagram ($U−V$ versus $M_V$) are preferentially (70%) located between the early–type/red–sequence galaxies. On the other hand, sources with $S < 0.08$ mJy have a Sersic indexes distribution that peaks at low values of $n$, indicating a low value for the bulge to disk ratio, with only $≈ 18\%$ of the sources with $n > 2.5$, and they are widely spread in the color–magnitude diagram, with $≈ 60\%$ of them not being an early–type/red–sequence galaxy.

In Figure ??, left panel, we show the fractional distribution of measured intrinsic absorbing columns of equivalent $N_H$ for sources with X–ray counterpart in the AGN luminosity range $L_{2−10} > 10^{42}$ erg s$^{-1}$ (see Paper III). We find that in this luminosity range $≈ 1/3$ of the sources are radio loud and $≈ 2/3$ radio quiet, where radio loud is defined as $log(R_X) > −2.9$ (with $R_X \equiv νL_ν(5\text{GHz})/L_{2−10}$). We also find find a weak anticorrelation of radio loudness as a function of intrinsic absorption, adding support to the finding that radio emission is not efficient in selecting more absorbed AGN.

In Paper IV we exploit our multiwavelength approach to resolve the faint radio number counts population. As shown in Figure 2, right panel, we find that the well–known flattening of the radio number counts below $≈ 1$ mJy is mostly due to star–forming galaxies, which are missing above $≈ 2$ mJy but become the dominant population below $≈ 0.1$ mJy. AGN exhibit the opposite behavior, as their counts drop at lower flux densities, going from 100% of the total at $≈ 10$ mJy down to $< 50\%$ at the survey limit. This is driven by the fall of radio–loud sources, as radio–quiet objects, which make up $≈ 20\%$ of sub–mJy sources, display relatively flat counts. Radio–quiet AGN make up about half of all AGN. Their counts appear to be a scaled down version, by a factor $≈ 3−4$, of those of
star–forming galaxies, and are very different from those of the radio–loud AGN population. This should provide a clue to the origin of their radio emission.

Star–forming galaxies make up $\lesssim 60\%$ of sub–mJy sources down to the flux limit of this survey. This has to be regarded as a robust upper limit, as whenever we had to make some assumptions, we choose to maximize their numbers. This result is at variance with the many papers, which over the years have suggested a much larger dominance of star forming galaxies below 1 mJy. On the other hand, our results are in broad agreement with a number of recent papers, which found a significant AGN component down to $\approx 50 \mu$Jy. The results of our model calculations (see Paper IV for details) agree quite well with the observed number counts and provide supporting evidence for the scenario described above. Moreover, they imply that sub–mJy radio–loud AGN are dominated by low–power, Fanaroff–Riley type I radio galaxies, as their high–power counterparts and radio–loud quasars are expected to disappear below $\sim 0.5 – 1$ mJy.

Figure 2. Left panel: fractional distribution of measured intrinsic absorbing columns of equivalent $N_\text{H}$ for sources with redshifts and $L_X > 10^{42}$ erg s$^{-1}$ (continuous histogram). The fractional distribution of absorbing columns of the entire X–ray sample is also shown (dashed histogram). The two distributions are consistent with each other. Right panel: the Euclidean normalized 1.4 GHz CDFS source counts: total counts (black triangles), SFG (filled green circles), all AGN (red squares), and radio-quiet AGN (open blue circles). Error bars correspond to 1σ errors. Model calculations refer to SFG (green dot-dashed lines), displayed with a 1σ range on the evolutionary parameters, all AGN (red dashed line), radio-quiet AGN (blue dotted line), and the sum of the first two (black solid line). See Paper IV for more details.

4. Conclusions

We have used a deep radio sample, which includes 266 objects down to a 1.4 GHz flux density of 42 $\mu$Jy selected in the Chandra Deep Field South area, to study the nature of sub–mJy sources. Our unique set of ancillary data, which includes reliable optical/near-IR identifications, optical morphological classification, redshift information, and X-ray detections or upper limits for a large
fraction of our sources, has allowed us to shed new light on this long standing astrophysical problem.

Summarizing, we suggest that the flux density bin $S \geq 0.08 \text{ mJy}$ is dominated by a population of early-type galaxies harboring low luminosity AGN, while only at flux densities below $\approx 0.08 \text{ mJy}$ starburst galaxies start to become dominant. Considering the apparent emerging population of low luminosity AGN at microjansky levels, care is needed when interpreting radio source counts in terms of the evolution of the star formation rate in the Universe.

We plan to expand on this work by using our deeper ($7 \mu\text{Jy per beam over the whole Extended CDFS region}$) radio observations (Miller et al. 2008) and the recently released 2 Msec Chandra data (Luo et al. 2008), to obtain additional contraints on the role of star forming galaxies as opposed to AGN in the sub–mJy radio population.

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