THE VLA SURVEY OF THE CHANDRA DEEP FIELD–SOUTH. II. IDENTIFICATION AND HOST GALAXY PROPERTIES OF SUBMILLIJANSKY SOURCES

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ABSTRACT

We present the optical and infrared identifications of the 266 radio sources detected at 20 cm with the Very Large Array in the Chandra Deep Field–South. Using deep i-band Advanced Camera for Surveys, R-band Wide Field Imager, K-band SOFI VLT, K-band ISAAC VLT and Spitzer imaging data, we are able to find reliable counterparts for 254 (≈95%) VLA sources. Twelve radio sources remain unidentified, and three of them are “empty fields.” Using literature and our own data we are able to assign redshifts to 186 (≈70%) radio sources: 108 are spectroscopic redshifts and 78 are reliable photometric redshifts. Based on the rest-frame colors and morphological distributions of the host galaxies, we find evidences for a change in the submillijansky radio source population: (1) above ≈0.08 mJy early-type galaxies are dominating and (2) at flux densities below ≈0.08 mJy, starburst galaxies become dominant.

Subject headings: cosmology: observations — galaxies: active — galaxies: starburst — radio continuum: galaxies

Online material: color figures, machine-readable table

1. INTRODUCTION

Deep radio surveys have shown that there is an upturn in the differential radio source counts below ≈1 mJy that cannot be reproduced by evolutionary models of the millijansky radio populations (e.g., Condon & Mitchell 1984; Windhorst et al. 1985; Ciliegi et al. 1999; Gruppioni et al. 1999; Richards et al. 2000; Seymour et al. 2004; etc.). Dedicated follow-up spectroscopic programs of many of these deep radio surveys (e.g., Thuan & Condon 1987; Prandoni et al. 2001; Afonso et al. 2005) have shown that the submillijansky sources are mainly identified with faint blue galaxies with disturbed morphologies indicative of interactions and merging activity. However, due to the faint magnitudes of a large fraction of these submillijansky sources, all these works are based on a small percentage of identifications. Interestingly, Gruppioni et al. (1999) has shown that even at the submillijansky level a large fraction of the radio sources are identified with early-type galaxies once the spectroscopic follow-up reaches a fainter magnitude limit.

The aim of this paper is to identify the radio sources in one of the best-studied regions of the sky, the Chandra Deep Field–South (CDF-S) and to study the properties of their host galaxies down to faint radio flux densities. The CDF-S area has been imaged with the Very Large Array (VLA) down to 8.5 μJy rms near the field center and 3.5″ resolution at both 1.4 and 5 GHz. The radio catalog include 266 sources. Details on the reduction process and the overall VLA data are reported in Kellermann et al. (2008; hereafter Paper I). The CDF-S region is the area of the sky with the most extensive multiwavelength observations available, covering an impressively wide range of wavelength. All of NASA’s existing Great Observatories (Hubble Space Telescope, Chandra, and Spitzer), ESA’s XMM-Newton and the Very Large Telescope at ESO have devoted hundreds of hours each to obtain state-of-the-art sensitivities in this field. The large amount of ancillary data made the VLA survey in the CDF-S extremely valuable in understanding better the properties of the submillijansky radio population. At the same time the radio data can help resolving uncertainties on the identification or the nature of sources selected at other wavelengths.

The paper is structured as follows: in § 2 we provide a general description of the ancillary data used in the identification process; in § 3 the identification methodology is described; we present in § 4 the identification catalog; in § 5 we report on some particular sources with problematic identification; § 6 describes the redshift distribution of the VLA sources; § 7 is devoted to the discussion of the properties of the host galaxies, and finally we summarize our conclusions in § 8.

We use in this paper magnitudes in the AB system, if not otherwise stated, and we assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. OPTICAL AND NIR DATA

While we refer the reader to Paper I for an overview of the multiwavelength coverage of the CDF-S area, in this section we describe the data sets used for the identification of the radio sources.

In the optical band, we used data obtained with the Advanced Camera for Surveys (ACS) on board HST and the Wide Field Imager (WFI) installed at the 2.2 m telescope in La Silla. A central area of 160 arcmin$^2$ (Fig. 1, dashed line) has been covered by ACS in four different filters: F435W (b), F606W (i), F775W (i), and F850LP (z). These data have been taken as part of The Great Observatories Origins Deep Survey (Dickinson et al. 2003; Giavalisco et al. 2004) down to the following limiting magnitudes (5 $\sigma$ in a 1 arcsec$^2$ area): 26.7, 26.7, 25.9, and 25.6. For our
identification purposes we used the F775W (i) band catalog, which is publicly available on the GOODS Web site. For the outer region of our VLA survey not overlapping with the GOODS-ACS area, we used the WFI R (652 nm) band images from the ESO Imaging Survey (EIS). These data cover the whole VLA survey down to a limiting magnitude of 25.5 (AB, 5σ in 2″ aperture).

In the NIR, we used the ISAAC VLT Ks (2162 nm) data from the GOODS survey on a central area of ~131 arcmin² (Fig. 1, solid line). The mean limiting magnitude of this observation is 24.7 (AB, 5σ in 1″ apertures; J. Retzlaff et al., in preparation). Finally, we have used shallower imaging in the Ks band obtained with SOFI NTT (21.4, AB, 5σ in 2″ aperture; Olsen et al. 2006) which covers the whole VLA survey.

The offsets between the radio catalog and each one of the optical/NIR catalogs has been computed using a sample of pointlike radio sources with S/N > 5 associated to a pointlike counterpart. In Figure 2 we show the ∆R.A. = R.A.(radio) − R.A.(optical/NIR) and ∆decl. = decl.(radio) − decl.(optical/NIR) in the case of the WFI-R catalog (Fig. 2, left) and SOFI-Ks catalog (Fig. 2, right). We found mean offsets of ∆R.A. = 0.20″ ± 0.06″ and ∆decl. = 0.09″ ± 0.08″ for WFI-R, and ∆R.A. = 0.13″ ± 0.04″, and ∆decl. = 0.12″ ± 0.06″ for SOFI-Ks. Similar offsets have been computed for the other catalogs (see Table 1). Before proceeding in the identification process, we correct for these mean offsets each one of the optical/NIR catalogs, in order to have radio and optical/NIR positions in the same reference frame.

3. IDENTIFICATION METHODOLOGY

Because of the faintness of both radio and optical samples, we could have more than one candidate counterpart for a single radio source. Therefore, we used the likelihood ratio technique which provides a reliability measure of an identification as a function of the distance of the counterpart and of its magnitude. This technique has been first used in this context by Richter (1975) and since by de Ruiter et al. (1977), Prestage & Peacock (1983), Windhorst et al. (1984), Wolstencroft et al. (1986), Sutherland & Saunders (1992), Ciliegi et al. (2003, 2005), and Brusa et al. (2005, 2007).

The likelihood ratio (LR) is the probability that a given source with offset r and measured magnitude m is the true counterpart, relative to the probability that the same object is a chance background source,

$$LR = \frac{q(m)f(r)}{n(m)},$$

where q(m) is the expected probability distribution as a function of magnitude of the true counterparts, f(r) is the probability distribution of the positional errors, and n(m) is the surface density
as a function of magnitude of background objects. We refer the reader to Ciliegi et al. (2003) for a detailed discussion on the procedure to calculate \(q(m)\), \(f(r)\), and \(n(m)\). In particular, to derive an estimate of \(q(m)\) we adopt a radius of \(2''\) to maximize the overdensity due to the presence of the optical/NIR counterparts (we expect that the majority of the true optical/NIR counterparts are inside a \(2''\) circle around the radio position). Inside \(f(r)\) both the radio and optical/NIR positional uncertainties are included. For the optical/NIR positional error we assume \(0.05''\) while for the radio uncertainties we use the values reported in Table 1 of Paper I.

In Figure 3 we show the distribution of the different components of equation (1) for the WFI-R catalog, specifically the magnitude distribution of background objects that we expect to have in the area where the search for counterparts is performed (Fig. 3, dashed-line histogram). This distribution is obtained multiplying the surface density as a function of magnitude of background objects, \(n(m)\), times the area of a circle of \(2''\) radius times the number of radio sources. The black-filled histogram is the magnitude distribution of possible counterparts found in circles of \(2''\) radius around the radio sources, and the gray-hatched histogram represents the expected magnitude distribution for the true optical counterparts once the background objects have been removed. We choose a threshold value for the likelihood ratio of \(LR_{th} = 0.2\), and we consider objects below this value as spurious counterparts.

We find that this value is a good compromise between having a low enough threshold to avoid missing many real identifications and large enough to have few spurious ones.

Apart from a LR value for each possible counterparts, we would like to have a measure of the reliability of a particular source to be the true counterpart. Sutherland & Saunders (1992) first pointed out that the presence or absence of other candidate counterparts for a single radio source provides additional information to that contained in LR and they developed a self-consistent formula for the reliability \(R_j\) of an object \(j\) to be the true counterpart,

\[
R_j = \frac{LR_j}{\sum_i LR_i (1 - Q)},
\]

where \(i\) runs over the set of all candidate counterparts for that particular radio source, and \(Q = \int_{q_{min}}^{q_{max}} q(m) dm\) is the probability that the counterpart of the source is above the magnitude limit of the optical/NIR catalog. We choose \(Q = 0.8\) corresponding to the ratio of the expected number of identification, the integral of \(q(m)\), and the total number of radio sources. We note that for values of \(Q\) in the range 0.5–1.0 there is no significant difference in the result of the identification process.

To summarize, we adopt the following criterion to choose the most likely counterpart for a radio source: (1) if only one candidate counterpart with \(LR > LR_{th}\) is available, this is chosen; (2) if there are several candidate counterparts with \(LR > LR_{th}\), we choose the one with the highest reliability (\(R_j\)) value. We call a radio source an “empty field” if it has no candidate counterpart within a distance of \(10''\) from the radio position.

4. IDENTIFICATIONS

We use four different catalogs (ACS-i, WFI-R, ISAAC-Ks, and SOFI-Ks) and the procedure outlined in the previous section to identify the counterparts of the VLA sources in the CDF-S area. In this section, we first report on the identification success rate for each one of these data sets and finally summarize the overall results of the identification process.

We find reliable counterparts for 67 (~85%) of the 79 radio sources inside the area covered by ACS GOODS. The expected number of true counterparts, given by the sum of the reliability (\(R\)) values for all sources with \(LR > LR_{th}\), is \(\sim 66.7\); therefore, we expect that less than one of the optical counterparts found from the ACS GOODS catalog could be spurious. We are not able to assign an optical counterpart to 12 radio sources of which four have a possible counterpart with \(LR < LR_{th}\), while eight appear as “empty fields” in the ACS images. The WFI-R catalog covers the all VLA image, and we find reliable counterpart for 230 (~86%) of the 266 radio sources. Of these we expect a maximum of three spurious identifications. The number of unidentified sources is 36, 12 of which are “empty field.” From the NIR catalogs, we are able to identify 56 (92%) of the 61 radio sources with ISAAC-Ks imaging, and we expect that less than one of these should be spurious. The shallower SOFI-Ks catalog covers the all VLA area, and it provides reliable counterparts for 190 (71%) of the 266 radio sources of which likely no more than six could be spurious. The surface density of NIR sources is lower compared to that of

| TABLE 1 |
| POSITIONAL OFFSETS BETWEEN THE RADIO AND THE OPTICAL/NEAR-IR CATALOGS |
| POSITION | OPTICAL | NIR |
| R.A. (arcsec) | WFI-R | ISAAC-K | SOFI-K |
| Decl. (arcsec) | 0.15 | 0.15 | 0.13 |

![Figure 3](https://example.com/image.jpg)
optical objects; therefore, we expect less spurious identifications due to background sources: one for ISAAC and two for SOFI.

Using the NIR catalogs, we are able to assign reliable counterpart to 18 radio sources that were not identified in the optical.

Finally, to maximize the number of radio sources identified, we consider two additional data sets. The Galaxy Evolution from Morphologies and SEDs program (GEMS; Rix et al. 2004) has imaged in two filters, F606W ($\lambda$) and F850LP ($\lambda$), with ACS the whole area covered by our radio survey. Using this data, we are able to find reliable counterparts for five radio sources previously unidentified (ID = 19, 46, 78, 176, 213). We also use the *Spitzer* (3.6, 4.5, 5.8, 8.5, 24 μm) images obtained as part of GOODS and the *Spitzer* MIPS (24 and 70 μm) observations performed as part of FIDEL12 (PI: M. Dickinson); from these mid-IR images, we find reliable counterparts for five additional radio sources (ID = 70, 87, 100, 105, 216).

Summarizing, from the optical, NIR catalogs, and including the additional identifications from GEMS and *Spitzer* data, we find reliable counterparts for 254 (~95%) of the 266 radio sources. The number of spurious identifications due to background objects is expected to be lower than eight. Twelve radio sources remain unidentified: three of them are empty fields, while the remaining nine have possible counterparts but with LR < LRth.

We summarize the output of the likelihood ratio process in Table 2.

| Source                  | Optical | NIR     |
|-------------------------|---------|---------|
| Radio Sources           | 79      | 266     |
| LR > LRth Counterparts  | 67      | 230     |
| LR < LRth Counterparts  | 4       | 24      |
| Percent Identified       | 85      | 86      |
| Possible Spurious        | <1      | 3       |
| Unidentified             | 12      | 36      |
| Empty Fields             | 8       | 12      |

| Source                  | ACS-i  | WFI-R  | ISAAC-K | SOFI-K | Total |
|-------------------------|--------|--------|---------|--------|-------|
| Radio Sources           | 79     | 266    | 61      | 266    | 266   |
| LR > LRth Counterparts  | 67     | 230    | 56      | 190    | 254   |
| LR < LRth Counterparts  | 4      | 24     | 1       | 12     | 9     |
| Percent Identified       | 85     | 86     | 92      | 71     | 95    |
| Possible Spurious        | <1     | 3      | <1      | 6      | 8     |
| Unidentified             | 12     | 36     | 5       | 76     | 12    |
| Empty Fields             | 8      | 12     | 4       | 64     | 3     |

* Number of radio sources inside the area imaged in the different bands.
* Number of radio sources with a counterpart with LR above the threshold LR > LRth and therefore considered reliable.
* Number of radio sources only with a counterpart with LR below the threshold LR < LRth and therefore considered unreliable.
* Percentage of identified sources (considering only counterparts with LR > LRth).
* Maximum number of spurious sources expected between the counterparts with LR > LRth.
* Number of radio sources without any counterparts or with counterparts with LR < LRth.
* Number of radio sources without any possible counterpart.

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**TABLE 2**

**OUTPUT OF THE LIKELIHOOD RATIO TECHNIQUE FOR THE RADIO SOURCES IDENTIFICATION**

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**Fig. 4.—** Left: Cumulative distribution of the radio to optical/NIR separations. The dashed line indicates a separation of 1.3" within which 90% of the counterparts are located. Right: Distribution of the reliability parameter, $R$, for the radio counterparts. The dashed line at $R = 0.83$ marks the reliability value above which 90% of the counterparts are located. [See the electronic edition of the Supplement for a color version of this figure.]

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12 See http://www.noao.edu/noao/fidel/.
We present in Table 3 the catalog for the optical/NIR identification of the radio sources in the VLA CDF-S area. The catalog is organized as follows.

Column (1).—The radio source number used in this paper (see also Paper I).

Columns (2)–(3).—The right ascension and declination (J2000.0) of the radio source (see also Paper I).

Columns (4)–(5).—The right ascension and declination (J2000.0) of the primary counterpart. The positional error is 0.05".

Column (6).—The separation, in arcseconds, between the radio source and its counterpart.

Column (7).—The likelihood ratio (LR) as defined in § 3.

Column (8).—The reliability parameter (R) as defined in § 3.

Column (9).—The catalog from which the counterpart was selected; ACS-i (i-band catalog from ACS GOODS), WFI-R (R-band catalog from WFI), ISAAC-K (K-band catalog from ISAAC), SOFI-K (K-band catalog from SOFI), GEMS (z-band catalog from ACS GEMS), SPITZER (IRAC and MIPS images).

Column (10).—The R-band magnitude (AB).

Column (11).—The K-band magnitude (AB).

Column (12).—The spectroscopic redshift of the counterpart.

Column (13).—Quality flag for the spectroscopic redshifts: “2” secure redshift (multiple spectral features), “1” tentative redshift (e.g., based on a single emission line).

Column (14).—The photometric redshift of the counterpart.

For some radio source we find more than one possible counterpart with LR > LR_th. We call the counterpart with the highest reliability value the primary (Table 3), and the remaining ones we call secondary. Table 4 contains the properties of these secondary counterparts.

For each one of the 266 radio sources we have produced an optical cutout (see Fig. 5) using the ACS-i GOODS images, the ACS-z data from GEMS, or finally, for those radio sources not covered by ACS, the WFI-R mosaic. The default size of the cutouts is $10''\times 10''$. We indicate the radio position (Fig. 5, cross), the primary counterpart (Fig. 5, square), and secondary counterpart (Fig. 5, circle).

As already mentioned, for 18 radio sources unidentified in the optical, a reliable counterpart is found in the NIR bands. Optical and K-band cutouts for these objects are shown in Figure 6.

Five radio sources are correctly identified only from the Spitzer observations in the CDF-S region. We show in Figure 7 their optical and Spitzer cutouts. The details of these five sources are the following.

RID 70: J033159.82−274540.3.—The most likely counterpart becomes visible only at 4.5 μm. This radio source is also in the ATCA 1.4 GHz survey (Afonso et al. 2006), ATCDFS J033159.86−274541.3, and the distance between the two radio coordinates is $\sim1''$. This source was unidentified in Afonso et al. (2006), since they limited the search for counterparts to the optical bands.

RID 87: J033209.90−275015.7.—The counterpart is clearly visible in all of the four IRAC bands.

RID 100: J033213.31−273934.1.—The counterpart is visible only in the 4.5 μm Spitzer image.

RID 105: J033215.39−275037.5.—The counterpart of this radio source becomes visible only in the Spitzer bands. This object is also detected with Chandra (XID = 587), and it was identified in Giacconi et al. (2002) with a $R = 21.0$ galaxy located at $\sim1.8''$ southwest of the X-ray position. We believe that this X-ray source has the same counterpart as the only chosen for the radio source. The spectroscopic redshift for XID = 587 of $z = 0.246$ reported by Szokoly et al. (2004) belongs to the old counterpart, while for the newly proposed counterpart we currently have only a photometric redshift estimate of $1.80 \pm 0.08$ (Grazian et al. 2006).
# TABLE 4

**Optical, Near Infrared Secondary Counterparts of the 20 cm Sources in the E-CDF-S**

| RID   | R.A. (J2000.0) | Decl. (J2000.0) | Dist. (arcsec) | LR | Rel. | Catalog | R (AB) | K (AB) | z  | Qual-z | z\_phot |
|-------|---------------|----------------|----------------|----|------|----------|--------|--------|----|--------|---------|
| 38... | 3 31 44.48    | −27 42 11.0    | 3 31 44.49     | 100| 0.74 | WFI-R   | 25.15  | >21.4  |    |        |         |
| 71... | 3 32 00.84    | −27 35 56.4    | 3 32 00.91     | 140| 1.00 | WFI-R   | 23.43  | >21.4  |    |        | 0.88 ± 0.06 |
| 98... | 3 32 13.19    | −27 57 44.4    | 3 32 13.25     | 1.10| 1.13 | WFI-R   | 24.77  | >21.4  |    |        |         |
| 101...| 3 32 13.52    | −27 49 52.5    | 3 32 13.46     | 0.80| 13.81| ACS-i   | 22.78  | 19.80 ± 0.01 | 0.731c | 2 | 0.69 ± 0.082 |
| 110...| 3 32 17.22    | −27 52 21.3    | 3 32 17.27     | 1.70| 0.75 | ACS-i   | 24.48  | 22.00 ± 0.04 | 1.097a | 2 | 0.34 ± 0.082 |
| 113...| 3 32 19.17    | −27 54 07.7    | 3 32 19.11     | 0.60| 44.02| ACS-i   | 24.08  | 20.40 ± 0.01 | 0.964a | 2 | 0.98 ± 0.082 |
| 118...| 3 32 21.00    | −27 47 06.3    | 3 32 21.05     | 1.50| 8.26 | ACS-i   | 23.08  | 21.34 ± 0.03 | 0.62 ± 0.082 |
| 120...| 3 32 21.29    | −27 44 35.6    | 3 32 21.32     | 1.10| 71.01| ACS-i   | 20.53  | 18.22 ± 0.01 | 0.524b | 2 | 0.49 ± 0.082 |
| 121...| 3 32 22.04    | −27 42 44.0    | 3 32 22.16     | 1.70| 1.94 | ACS-i   | 24.15  | 22.38 ± 0.07 | 1.877d | 1 | 1.78 ± 0.082 |
| 121...| 3 32 22.04    | −27 42 44.0    | 3 32 22.05     | 2.00| 0.70 | ACS-i   | 24.98  | >24.7  |    |        | 0.66 ± 0.082 |
| 126...| 3 32 22.68    | −27 41 26.1    | 3 32 22.85     | 2.60| 0.62 | ISAAC-K | 24.70  | 21.78 ± 0.04 | 2.02 ± 0.082 |
| 136...| 3 32 27.97    | −27 46 39.4    | 3 32 28.00     | 1.60| 2.21 | ACS-i   | 22.72  | 22.08 ± 0.01 | 0.04 ± 0.082 |
| 145...| 3 32 31.47    | −27 46 23.3    | 3 32 31.41     | 1.90| 0.51 | ACS-i   | 23.89  | 23.01 ± 0.09 | 2.223a | 2 | 0.75 ± 0.082 |
| 160...| 3 32 37.29    | −27 51 27.4    | 3 32 37.17     | 1.50| 17.19| ACS-i   | 22.48  | 19.58 ± 0.01 | 1.01 ± 0.082 |
| 161...| 3 32 37.79    | −27 50 00.4    | 3 32 37.76     | 1.10| 6.68 | ACS-i   | 23.95  | 21.83 ± 0.03 | 1.004e | 1 | 1.00 ± 0.082 |
| 162...| 3 32 37.80    | −27 52 12.4    | 3 32 37.92     | 1.90| 0.37 | ACS-i   | 24.18  | >24.7  | 1.603a | 2 | 0.69 ± 0.082 |
| 164...| 3 32 38.80    | −27 44 49.2    | 3 32 38.66     | 1.70| 0.26 | ACS-i   | 26.30  | >24.7  |    |        | 0.06 ± 0.082 |
| 169...| 3 32 39.47    | −27 53 01.3    | 3 32 39.47     | 0.70| 197.29 | ACS-i | 21.25  | 19.15 ± 0.01 | 0.68 ± 0.082 |
| 170...| 3 32 39.68    | −27 48 51.4    | 3 32 39.55     | 1.60| 1.95 | ACS-i   | 24.84  | 21.81 ± 0.03 | 3.064a | 2 | 3.06 ± 0.082 |
| 177...| 3 32 43.16    | −27 55 14.3    | 3 32 43.26     | 1.80| 0.28 | ACS-i   | 23.83  | 21.44 ± 0.31 | 0.579d | 2 |         |
| 192...| 3 32 48.59    | −27 49 34.4    | 3 32 48.51     | 1.10| 0.99 | ACS-i   | 24.64  | 21.09 ± 0.02 | 1.117e | 2 | 1.11 ± 0.082 |
| 215...| 3 33 03.22    | −27 53 06.1    | 3 33 03.29     | 1.20| 5.06 | WFI-R   | 23.65  | 20.06 ± 0.06 | 0.82 ± 0.061 |
| 227...| 3 33 07.75    | −27 53 51.0    | 3 33 07.70     | 0.90| 1.32 | WFI-R   | 24.87  | >21.4  |    |        |         |
| 251...| 3 33 20.93    | −27 47 56.4    | 3 33 21.20     | 4.90| 0.29 | WFI-R   | 21.66  | >21.4  |    |        |         |
| 262...| 3 33 36.45    | −27 43 55.5    | 3 33 36.37     | 1.80| 0.35 | WFI-R   | 23.92  | >21.4  |    |        | 1.11 ± 0.091 |

a Spectroscopic redshift from Szokoly et al. (2004). The average redshift uncertainty is Δz = 0.005.
b Spectroscopic redshift from Silvermann et al., in preparation.
c Spectroscopic redshift from Vanzella et al. (2005, 2006, 2008). The average redshift uncertainty is Δz = 0.00055.
d Spectroscopic redshift from Popesso et al. (2008).
e Spectroscopic redshift from Le Fevre et al. (2004). The average redshift uncertainty is Δz = 0.0012.
f Photometric redshift from Wolf et al. (2004).
g Photometric redshift from Grazian et al. (2006).
Fig. 5.—Cutouts of the radio sources either from ACS (GOODS-i, GEMS-z), or WFI-R. Each one is $5\arcsec$ on a side. The cross indicates the radio position, the square indicates the primary counterpart, while the triangles are possible secondary counterparts. [See the electronic edition of the Supplement for a color version of this figure.]
RID 216: J033303.30–275328.0.—The most likely counterpart is visible only in the 3.6 μm Spitzer image.

We show in Figure 8 the $R$-magnitude distribution for the primary counterparts (Figure 8, histogram). We highlight sources with a spectroscopic redshift (Fig. 8, black shading) and the ones with a photometric redshift (Fig. 8, gray shading). It is clear from this plot how the ability to obtain a redshift for the optical counterparts decreases going to fainter magnitudes: $\sim88\%$ of the objects with $R_{AB} < 24$ have a redshift (spectroscopic or photometric) while this fraction decreases to $\sim30\%$ for sources with $R_{AB} > 24$.

5. NOTES ON PARTICULAR SOURCES

Some of the identifications presented need further discussion due to a complex appearance either in the optical/NIR or in the radio band. Cutouts of each of these sources are shown in Figure 9.
The component letters in this section refer to radio source components as given in Table 1 of Paper I.

RID 7: J033115.06–275518.4.—This complex multicomponent radio source is identified with an $R \sim 21$ optical/NIR galaxy coincident with component B.

RID 18: J033127.23–274247.6.—A possible blending of two sources, the counterpart, a $R = 24$ galaxy, coincident with the component A.

RID 23: J033130.05–273814.2.—Assuming that the central component is the core of a double-lobed objects, we tentatively identified the radio source with a faint ($R \approx 26$) optical source.

RID 30: J033138.56–273808.8.—The faint radio source ($S_{14} = 175 \mu$Jy) is extended toward the faint galaxy to the southwest. It is likely a blend of two faint sources with the southwest one identified with the counterpart we have given in our catalog.

RID 50: J033150.35–274119.1.—The counterpart ($R = 23.9$) listed in Table 3 is close to the peak of the radio emission and is
relatively red ($K_S = 20.6$), while an extension of the radio emission points south to a $\sim 3''$ distant spiral galaxy ($R = 21.5$). The photometric redshift from COMBO-17 reported in Table 3 could be affected by the contamination in the optical bands of a nearby ($\sim 1.3''$) source.

 RID 60: J033154.90–275340.5.—Probably the blend of two radio sources. Currently, in Table 3 is listed the possible counterparts, $R = 24.5$, for one of the two sources; the other blended radio source could be identified with a $R = 21.3$ galaxy with an offset of $\sim 3''$ from the radio centroid.

 RID 113: J033219.17–275407.7.—This is a powerful extended double lobed radio source (Fanaroff and Riley type II). We choose as the most likely counterpart the secondary according to our method based on LR (Fig. 9, blue triangle in inset). The same

Fig. 6—Continued

Fig. 7.—Cutouts of the radio sources identified in the Spitzer bands. For each of these sources, we show the optical (left) and IR (right) cutouts. Each one is 10'' on a side. The cross indicates the radio position, the square indicates the primary counterparts, while the triangles are possible secondary counterparts. [See the electronic edition of the Supplement for a color version of this figure.]
counterpart was also chosen for the X-ray source 249 (Giacconi et al. 2002). Higher resolution is needed to be certain of the optical counterpart. Another X-ray source from Giacconi et al. (2002) XID = 527 is coincident with the bright peak on the southwest radio lobe (component C); not surprisingly this X-ray source was unidentified.

RID 122: J033222.49−274805.4.—This radio source is identified with a $K = 22.8$ galaxy located at ~0.5″ from the VLA position. This counterpart is not visible in the optical bands but is brighter in the NIR and in all the four IRAC Spitzer bands. This object is also detected with Chandra (XID = 570 from Giacconi et al. 2002), and it was identified with a $R = 24.6$ galaxy located ~1.2″ northeast of the X-ray position. We propose that this X-ray sources is identified with the same counterpart of the radio source. This radio source is also part of the ATCA 1.4 GHz catalog presented by Afonso et al. (2006) ATCDFS J033222.36−274807.3, and the distance between the two radio positions is ~2.6″. In their catalog, this source remains unidentified, we note that our $K$-band counterpart candidate is ~4″ from the Afonso et al. (2006) radio position.

RID 140: J033228.83−274356.4.—This source is identified with an $I \sim 18.3$ galaxy 0.6″ from the central radio component (RID 140A). This identification is also supported by an X-ray detection (XID = 103 from Giacconi et al. 2002). We note that Afonso et al. (2006) reported a radio source, ATCDFS J033228.71−274402.3, ~7″ away from our radio position. This ATCA source remained unidentified, and in our catalog, we believe this was due to the less accurate position provided by the ATCA survey as compared to ours. Finally, another X-ray detection, XID = 630 from Giacconi et al. (2002) was tentatively identified with a $R \approx 23$ galaxy, we suggest that is instead associated with the south component of this radio jet (B).

RID 169: J033239.47−275301.3.—This radio source is associated with a pair of interacting galaxies. One of the galaxies has a spectroscopic redshift of $z = 0.686$ (Vanzella et al. 2005), while the other has a photometric redshift estimate of $z_{\text{phot}} = 0.65 \pm 0.01$ from COMBO-17.

RID 176: J033242.57−273816.4.—A double lobe radio galaxy. The likely core is clearly visible at 4.5 μm with Spitzer.

RID 178: J033244.20−275142.1.—This radio source is probably the blend of two objects (A and B) that correspond to a couple of interacting galaxies at $z = 0.279$ (Szokoly et al. 2004). The counterpart of 178A has a high-excitation emission lines from the optical spectrum typical of an active galactic nucleus (AGN) and is also an X-ray source (XID = 98; Giacconi et al. 2002).

RID 186: J033246.83−274215.1.—This $S_{20cm} \sim 122$ μJy radio source is offset from the center of a bright ($R \approx 16.3$) galaxy. An X-ray source (XID = 84; Giacconi et al. 2002) is coincident with the centroid of the galaxy.

RID 207: J033257.08−280209.7.—The optical counterpart of this bright extended double radio source also coincides with an X-ray detection (XID = 508; Lehmer et al. 2005). The galaxy could be the central CD galaxy of a group/cluster of galaxies at $z = 0.664 \pm 0.001$ (photometric redshift from COMBO-17) and several arclike structures can be clearly seen in the ACS image (see inset in the cutout).

RID 215: J033303.22−275306.1.—The radio emission is coming from two interacting galaxies with consistent estimates of the photometric redshifts from COMBO-17, $z_{\text{phot}} = 0.73 \pm 0.10$, and $z_{\text{phot}} = 0.82 \pm 0.06$.

RID 244: 245-248.—These three radio sources could be one single source with two lobes. We note that RID = 248 has a possible counterpart (mag $R \sim 24$, distance ~0.8″) with LR > LRth, which is not consistent with it being a lobe of the radio source, but it could be the base of a jet which includes RID 244 and 245.

We are not able to find any counterpart for the following radio sources (see Fig. 10).

RID 97: J033213.09−274350.7.—This bright radio source ($S_{20cm} = 1.42$ mJy) remains unidentified although it is inside the GOODS area and therefore covered by deep ACS, ISAAC, and Spitzer imaging. This radio source corresponds to ATCDFS J033213.08−274351.0 of Afonso et al. (2006). We considered the possibility that RID 92 and RID 97 might be lobes of a double radio galaxy. RID 92 lies 38″ away. However, RID 92 appears to be firmly identified with an $R \sim 22$ galaxy, 0.2″ from the radio position and coincide with an X-ray source, so this interpretation is unlikely. RID 97 is slightly resolved, but about half of the flux density appears to be in an unresolved component, suggesting that it is an isolated source. However, we cannot exclude the possibility that RID 97 is part of RID 92, although there is no evidence of a connection between the two sources.

RID 155: J033235.02−275435.2.—This source ($S_{20cm} = 0.25$ mJy) remains unidentified, although it is inside the GOODS area and therefore covered by deep ACS, ISAAC, and Spitzer imaging.

RID 202: J033252.54−275942.9.—This radio source ($S_{20cm} = 0.1$ mJy) remains unidentified. It is outside the GOODS area and therefore is not covered by the deep IR imaging by ISAAC and Spitzer.

6. REDSHIFT DISTRIBUTION

We have compared the primary counterparts found in § 4 with the spectroscopic catalogs available in the CDF-S area. A total of 108 (∼41%) radio sources have a spectroscopic redshift. Thirty-six redshifts are provided by the follow-up campaign of the X-ray
sources in the CDF-S (Szokoly et al. 2004), seven from the FORS-2 GOODS program (Vanzella et al. 2005, 2006, 2008), 25 from the VIMOS GOODS program (Popesso et al. 2008), six from the VVDS survey (Le Fèvre et al. 2004), two from the spectroscopic follow up of the K20 survey (Mignoli et al. 2005), 31 from the optical follow up of the X-ray sources in the E-CDF-S (J. Silverman et al., in preparation), and one from Ravikumar et al. (2007). We report in column (12) of Table 3 these spectroscopic redshifts and in column (13) a quality flag for these measures. Since each spectroscopic survey has its own redshift quality flag system, we try to homogenize and simplify these different definitions using the following scheme: "2" secure redshift obtained using multiple spectral features, "1" tentative redshift (e.g., based on a single emission line).

For radio sources with no spectroscopic information available, we collected photometric estimates of their redshifts. Because of the deep and wide photometry available in this region of the sky, reliable photometric redshifts have been produced. Almost the entire area of the VLA observations is covered by the COMBO-17 survey which provides extremely accurate photometric redshifts using photometry in 17 passbands from 350 to 930 nm (Wolf et al. 2004). We use this data set with two limitations. We consider only COMBO-17 sources with \( R < 24 \) (Vega); at these magnitudes the errors on the photometric redshift estimates are expected to be less than \( \frac{z_{\text{phot}} - z_{\text{spec}}}{1 + z_{\text{spec}}} \approx 0.06 \). The COMBO-17 data for galaxies fainter than \( R = 24 \) (Vega) are too shallow. Furthermore, we limit the use of COMBO-17 photometric redshifts to \( z < 1.2 \), because at higher redshifts the COMBO-17 estimates become...
increasingly inaccurate due to the lack of NIR coverage (see § 4.6 of Wolf et al. 2004). We have waived this last constraint for objects best fitted with a QSO templates \( MC_{\text{class}} = \text{QSO} \) in Wolf et al. 2004) for which the photometric redshifts are accurate at least to \( z \approx 4 \) (see Fig. 18 of Wolf et al. 2004). We compare our catalog with Zheng et al. (2004) that has derived photometric redshifts for a large fraction of the X-ray sources in the CDF-S area and the GOODS-MUSIC catalog (Grazian et al. 2006) in which are published photometric redshifts obtained using the excellent optical and NIR data in the GOODS region. In total we are able to assign photometric redshifts to 78 radio sources without spectroscopic measures: 66 from COMBO-17, nine from GOODS-MUSIC, and three from Zheng et al. (2004). In order to check the accuracy of these photometric redshifts, we select only sources with a secure spectroscopic redshift (Col. 13 of Table 3 equal to 2) leading to a sample of 80 objects. In Figure 11 (left) we plot the difference between the photometric and spectroscopic redshift. The photometric redshifts are extremely precise with a \( \frac{z_{\text{phot}} - z_{\text{spec}}}{1 + z_{\text{spec}}} < 0.1 \) for almost all the objects. Only three sources have larger errors: RID 221, 230, 259. The spectra of RID 221 does not leave any doubt on the correctness of the spectroscopic redshift (clear Ca H and K lines), and its photometry does not seem to be affected by nearby sources. Similarly, a further inspection of the optical spectra of RID 230 and 259 confirms the spectroscopic redshift \( z = 1.029 \) (broad Mg ii and C ii] emission lines) and \( z = 0.860 \) ([O ii] and [O iii] emission lines), respectively. Nevertheless, for two of these sources the disagreement between photometric and spectroscopic redshift is small (\( \sim 0.1 \)). Clipping these three “outliers” out, we obtain an \( \text{rms} = 0.013 \) for \( \frac{|z_{\text{phot}} - z_{\text{spec}}|}{1 + z_{\text{spec}}} \).
The redshift distribution of the radio sample is plotted in Figure 11 (right): spectroscopic redshifts are shown as a filled histogram, the total histogram includes also photometric redshifts. In an inset of the same figure we show a zoom-in of the region 0.6 < z < 1.7 using a finer binning in the histogram (Δz = 0.02). We note that radio sources are good tracers of large-scale structures already detected at other wave bands in this region of the sky (NIR: Cimatti et al. 2002; optical: Le Fevre et al. 2004, Vanzella et al. 2005; X-ray: Gilli et al. 2003, Szokoly et al. 2004). The more prominent spikes in our redshifts distribution are at

![Fig. 10.— Cutouts of the three sources without any counterpart. In each cutout is indicated the source identification number (top left), the band (top right), the 1 σ magnitude limit (bottom left), and the dimensions of the cutout (bottom right). [See the electronic edition of the Supplement for a color version of this figure.]](image1)

![Fig. 11.— Left: Photometric redshift errors as a function of redshift. The dashed line indicates the value of z = 1.2 to which we limit our use of this data set. Right: Redshift distribution for the VLA CDF-S sample. The total histogram is obtained using both spectroscopic (49) and photometric (110) redshifts, while the shaded histogram refers only to the spectroscopic one. The inset is a zoom in the region 0.6 < z < 1.7 with a redshift bin of 0.02. The vertical dashed lines shows the location of three redshift spikes reported by Gilli et al. (2003) at z = 0.67, 0.73, 1.61. [See the electronic edition of the Supplement for a color version of this figure.]](image2)
z = 0.735 ± 0.004 (10 objects, four of these are also X-ray sources from Giacconi et al. 2002) and z = 1.614 ± 0.011 (six objects, two of these are also X-ray sources from Giacconi et al. 2002). Both these structure were traced in the X-rays (Gilli et al. 2003), respectively with 19 and 5 X-ray sources. Of the two prominent large-scale structures discovered in the X-ray survey, at z = 0.67 and z = 0.73, the radio sources are tracing only the second. As noted by Gilli et al. (2003) while the structure at z = 0.73 is dominated by a standard galaxy cluster with a significant concentration around a central CD galaxy, the one at z = 0.67 appears to be a rather loose structure uniformly distributed in the field.

7. HOST GALAXY PROPERTIES

In this section we investigate the properties of the host galaxy as a function of the 1.4 GHz flux density of the radio source. We want in particular, to study the behavior of three observables as a function of the radio flux density: (1) redshift, (2) morphology, and (3) rest-frame colors of the host galaxies. We are motivated by the known upturn in the normalized source count at 1.4 GHz below 3 mJy compared to the extrapolation from brighter flux densities (e.g., Fig. 7 in Paper I). This is generally modeled by the mix of two populations of sources: AGN and starburst galaxies. Several models (e.g., Seymour et al. 2004) predict that the starburst galaxies become dominant at 1.4 GHz flux densities below ~0.2 mJy. Further discussion on the source population properties will be presented by P. Padovani et al. (2009, in preparation, hereafter Paper IV). We divide our sample in three flux density bins with approximately the same number of sources: S < 0.08 mJy (91 objects), 0.08 < S < 0.2 mJy (83 objects), and S > 0.2 mJy (92 objects).

7.1. Redshift

In the three flux density intervals defined above respectively 71 (~78%), 56 (~67%), and 64 (~69%) objects have a redshift (spectroscopic or photometric). We show in Figure 12 (left) the redshift distributions of the three subsamples. The brighter objects (Fig. 12, solid line) are almost all at z < 1.5. Because of the small area of our VLA survey, we are missing the population of radio-loud QSOs that dominate this regime, as we know from shallower large-area radio surveys. The intermediate-flux density bin (Fig. 12, hatched histogram) shows a redshift distribution similar to the above one with a few objects at z ~ 4. A K-S test confirms with a probability of 46% that the two distributions are drawn from the same one.

Finally, the redshift distribution for the sources in the faintest bin (Fig. 12, shaded histogram) has a tail at higher redshift (~16% have z > 1.5). Previous surveys (e.g., Windhorst et al. 1995; Richards et al. 1998, 1999; Ciliegi et al. 2005) found that the majority of the µJy radio sources are at low (z < 1) redshifts. If we consider our faintest flux density bin, 22% of the objects are at z > 1, and for another 22% of sources we do not have any redshift information. The fraction of sources at z > 1 could grow up to 44% if all the unidentified objects are at high redshift. A K-S test gives a probability of 99% that the redshift distributions of the faintest and intermediate flux density bins are drawn from the same one.

7.2. Morphology

In this section we investigate the morphological properties of the host galaxies. The area of our VLA observations is almost entirely covered by the GEMS survey (Rix et al. 2004). The GEMS team has made publicly available13 (Häußler et al. 2007) a catalog containing the Sersic index (n) parameter (Sersic 1968) obtained using GALFIT (Peng et al. 2002). We consider only objects in this catalog with CONSTR_FLAG = 1 and SCIENCE_FLAG = 1 (see Häußler et al. 2007). Applying these constraints, we are left with 60 (S < 0.08 mJy), 48 (0.08 < S < 0.2 mJy) and 34 (S > 0.2 mJy) objects, respectively. We are therefore able to study the morphological properties of ~66%, ~58%, and ~37% of the objects in each flux density bin. The distributions of Sersic indexes are shown in Figure 12 (right). It has been empirically found that a Sersic index n = 2.5 (Fig. 12, vertical line) can roughly discriminate between early-type galaxies and late-type galaxies (e.g., Blanton et al. 2003; Shen et al. 2003; Hogg et al. 2004). Galaxies with n > 2.5 are generally early-type, while the majority of galaxies with n < 2.5 are late-type. We find that for the high- and intermediate-flux density bins (Fig. 12, histograms) the distribution of Sersic index is relatively flat with ~55% of

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13 See http://www.mpia.de/GEMS/gems.htm.
Fig. 13.—Image cutouts (10'' x 10'') of sources belonging to the four morphological classes defined in § 7: E (top), S0 (second row), S (third row), and I (bottom).
the objects with \( n > 2.5 \). According to a Kolmogorov-Smirnov (K-S) test these two distributions are drawn from the same one. Instead, the distribution of Sersic indexes appears completely different for the faintest flux density bin (Fig. 12, shaded histogram) with only \( \approx 18\% \) of the sources with \( n > 2.5 \). A K-S test gives a probability as low as \( \approx 0.05\% \) that the distribution for the faintest flux density bin and any of the other two are drawn from the same sample. This is suggesting that at \( \approx 0.08 \) mJy there is a significant change in the radio population with late-type galaxies becoming dominant. We are aware of the fact that using only the Sersic index to divide galaxies in morphological classes could produce a mixture of different galaxy populations (e.g., Sargent et al. 2008). Therefore, we visually classified our radio sources in four broad morphological categories: elliptical (E), lenticular (S0), spiral (S), and irregular (I). We show examples for these four categories in Figure 13. We are able to classify 161 (60\%) of the 266 radio sources. In Figure 14 (left) we show the distribution of Sersic index values for E+S0 (Fig. 14, hatched histogram) and S+I (Fig. 14, shaded histogram). The distributions of Sersic indexes are clearly different for these two classes of objects (K-S probability \( \approx 10^{-66} \)): E+S0 tend to have high value of \( n \), while S+I peak at \( n < 2.5 \). This plot confirms that our visual morphological classification is robust and at the same time is reassuring about the use of Sersic index to separate early- and late-type galaxies. We can now use this visual morphological classification to study the evolution of the host galaxy properties as a function of the \( S_{1.4\text{GHz}} \) flux density. In Figure 14 (right) we plot the percentages of early-type (E+S0), spiral, and irregular galaxies in the three flux density bins. While a large fraction of radio sources with \( S_{1.4\text{GHz}} > 0.08 \) mJy are early-type, at lower flux densities late-type galaxies become 5 times more numerous than elliptical or lenticular galaxies.

### 7.3. Rest-Frame Colors

We finally consider the rest-frame colors of our radio sources. We compare the list of optical/NIR counterparts presented in this work with the COMBO-17 photometric catalog (Wolf et al. 2004). We include only COMBO-17 sources with \( R \) magnitudes brighter that 24 (Vega), and we exclude sources classified as “QSO” from the SED fitting. We further exclude sources with broad (\( >2000 \) km s\(^{-1} \)) emission lines in their optical spectra to avoid contamination by the central AGN. Removing any other potential AGN according to the criterium \( L_{X}(0.5 - 10 \text{keV}) > 10^{42} \text{ergs s}^{-1} \) does not change the result. We finally exclude sources for which the COMBO-17 redshift (which has been used to compute the rest-frame colors by Wolf et al. 2004) is not in agreement with an available spectroscopic one. We obtain rest-frame colors for 47 (\( S > 0.2 \) mJy), 41 (\( 0.08 < S < 0.2 \) mJy), and 49 (\( S < 0.08 \) mJy) objects, respectively. In Figure 15 (left), we plot the rest-frame \( U - V \) colors as a function of the absolute magnitude \( M_{r} \) for radio sources with \( S > 0.2 \) mJy (Fig. 15, circles), \( 0.08 < S < 0.2 \) mJy (Fig. 15, triangles), \( S < 0.08 \) mJy (Fig. 15, stars) and optically selected galaxies from COMBO-17 (Fig. 15, gray dots). The distribution of rest-frame colors for the faintest radio flux density bin appears clearly different from the other two: while sources with \( S > 0.2 \) mJy are mainly concentrated in the top part of the plot, below 0.08 mJy the host galaxies are widely spread in the color-magnitude diagram. The dashed line in Figure 15 (left) is the empirical redshift-dependent color divisions that separate blue and red galaxies population. Following Bell et al. (2004), we define red-sequence/early-type galaxies as being redder than (\( U - V \)) = 1.15 − 0.31(z − 0.08(M_{r} − 5 \log H + 20), where \( z = 0.85 \), the average redshift of our radio sample. We find that \( \approx 70\% \) of the radio sources in the two brighter flux density bins are red-sequence galaxies while this percentage decreases to \( \approx 40\% \) for sources with \( S < 0.08 \) mJy. Again, we have an indication that early-type galaxies are the dominant population of the intermediate radio flux density bin, while late-type galaxies becomes dominant at the faintest radio flux densities. A K-S test on the distributions of the \( U - V \) colors (see Fig. 15, right) provides a probability as low as \( 0.5\% \) for the \( S < 0.08 \) mJy colors being similar to the ones of brighter radio sources.

Recently, Bondi et al. (2007) found that between 0.15 and 0.5 mJy the median radio spectral index is significantly flatter compared to brighter or fainter sources and they interpreted this as evidence that a population of flat spectrum low-luminosity compact AGNs and radio quiet QSOs is dominating the radio emission in this flux density range, while a starburst population is expected to have a steeper spectral index. At the same time, they confirm that early-type galaxies have spectral index significantly flatter than starburst ones. The Bondi et al. (2007) results are consistent with our finding that the majority of radio sources with flux

![Figure 14](https://example.com/fig14.png)

**Fig. 14.** — *Left*: Distribution of Sersic index values for sources with visual morphological classification “E” or “S0” (hatched histogram) and “S” or “I” (shaded histogram). *Right*: Percentages of E+S0, S, I, and unclassified sources in the three radio flux density intervals defined in § 7. [See the electronic edition of the Supplement for a color version of this figure.]
densities $0.08 < S < 0.2$ mJy are hosted in bulge dominated early-type host galaxies while at lower radio flux densities ($S \leq 0.08$ mJy) the starburst galaxies become dominant.

8. CONCLUSIONS

We have used a likelihood ratio technique to identify the 266 radio sources from the VLA survey in the CDF-S. Using the available imaging in $i, R, K_s$, 3.6, 4.5, 5.8, 8.5, 24, and 70 $\mu$m bands we were able to find a reliable counterpart for 254 ($\sim$95%) radio sources. Using literature data and our own follow up, a total of 186 ($\sim$70%) sources have a redshift: 108 are spectroscopic redshifts and 78 reliable photometric redshifts. The ability of obtaining a redshift (either spectroscopic or photometric) is a strong function of the magnitude of the counterparts: $\sim$88% of the objects with $R_{AB} < 24$ have a redshift while this fraction decreases to $\sim$30% for sources with $R_{AB} > 24$. The redshift distribution of the VLA sources peaks around $z \approx 0.9$. The radio sources are good tracers of large-scale structures already detected at other wave bands 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).

We have studied the properties of the host galaxies of the radio sources dividing the sample in three flux density bins equally populated: $S > 0.2$, $0.08 < S < 0.2$, and $S < 0.08$ mJy. 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 bright flux density bins:

1. show a Sersic indexes distribution that resembles that of early-type galaxies with a tail of disk dominated galaxies,
2. according to a visual morphological classification are mainly elliptical or lenticular galaxies,
3. in a rest-frame color-magnitude diagram ($U - V$ vs. $M_V$) are preferentially (70%) located between the early-type/red-sequence galaxies, while sources with $S < 0.08$ mJy:
4. have a Sersic indexes distribution that peaks at low values of $n$, indicating a low value for the bulge to disk ratio, with only $\approx$18% of the sources with $n > 2.5$,
5. are 5 times more likely to be hosted in a late-type galaxy instead of an elliptical or lenticular one,
6. are widely spread in the color-magnitude diagram, with $\approx$60% of them not being an early-type/red-sequence galaxy.

Summarizing, we suggest that the flux density bin $S \geq 0.08$ mJy is dominated by a population of early-type galaxies while at flux densities below $\approx 0.08$ mJy starburst galaxies become dominant.

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