THE DEEP SWIRE FIELD. II. 90 cm CONTINUUM OBSERVATIONS AND 20 cm–90 cm SPECTRA

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ABSTRACT

We present one of the deepest radio continuum surveys to date at a wavelength $\gtrsim 1$ m. The observations were taken with the VLA at 324.5 MHz covering a region of the SWIRE Spitzer Legacy survey, centered at $10h46m00s$, 59°01’00” (J2000). The data reduction and analysis are described and an electronic catalog of the sources detected above 5σ is provided. The spectral indices for 90 cm selected sources, defined as $S \propto \nu^{-\alpha}$, shows a peak near 0.7 and only a few sources with very steep spectra, i.e., $\alpha_{90} > 1$. The large population of very steep spectrum $\mu$Jy sources seems to exist down to the limit of our survey. For 20 cm selected sources, we find similar mean spectral indices for sources with $S_{20} > 1$ mJy. For weaker sources, below the detection limit for individual sources at 90 cm, we use stacking to study the radio spectra. We find that the spectral indices of small ($< 3'')$ 20 cm selected sources with $S_{20} < 10$ mJy have mean and median $\alpha_{20} \sim 0.3–0.5$. This is flatter than the spectral indices of the stronger source population. At the low end of the 20 cm survey, the spectral indices appear to be steepening again. We report log $N – \log S$ counts for 90 cm which show a flattening below 5 mJy. Given the median redshift of the population, $z \sim 1$, the spectral flattening and the flattening of the log $N – \log S$ counts occur at radio luminosities normally associated with active galactic nuclei rather than with galaxies dominated by star formation.

Key words: cosmology: observations – galaxies: active – galaxies: evolution – galaxies: general – galaxies: starburst

Online-only material: machine-readable and VO tables

1. INTRODUCTION

We are building a deep multiwavelength picture of the sky in the SWIRE Spitzer deep field, 1046+59, which was chosen to be ideal for deep radio imaging. In Paper I (Owen & Morrison 2008) we discussed the 20 cm continuum survey. The present 90 cm survey allows us to study the radio spectra of the general source population. For Jansky and mJy sources, very steep radio spectra often are associated with very high redshifts, although the physical origin of this effect remains unclear (e.g., Miley & De Breuck 2008). A large population of very steep spectrum, $\mu$Jy sources might suggest a corresponding high-redshift $\mu$Jy population. On the other hand, flatter radio spectra are often thought to be connected with synchrotron self-absorption or free–free absorption, although other mechanisms could potentially produce such spectra. Combined with other information the low-frequency spectral energy distribution has the potential to give us unique insight on the physics of black-hole-driven active galactic nuclei (AGNs) and star-forming galaxies. In this paper, we report our 90 cm observations with the VLA and some analysis of these radio data combined with our 20 cm survey of the same field from Paper I. In future papers in this series, we will combine these data with redshift measurements and observations at other wavelengths.

2. OBSERVATIONS, REDUCTION, AND CATALOGING

Observations were made of a single pointing center position, $10h46m00s$, 59°01’00” (J2000), with the VLA in A and C configurations for a total of almost 85 hr on-source between 2006 February and 2007 January. However, due to the ongoing EVLA upgrade, only 22 working antennae were typically available in A and 18 in C. Thus the total integration time was equivalent to $\sim 63$ hr in A and $\sim 5$ in C, with correspondingly less $uv$ coverage. In Table 1, we summarize the parameters of the observing runs. Since the total time is dominated by the A configuration, the final image for analysis had a resolution $\sim 6''$ and FWIWHM FOV of 2.3. The data were all taken in spectral-line mode 4 using online Hanning smoothing, resulting in fifteen 390.625 kHz channels in each of two IFs (centered at 321.5 and 327.5 MHz) and each of two polarizations. Five second integration times were used in the A configuration and 10 s in C. The integration times and channel bandwidths were chosen to minimize tangential and radial smearing of the images away from the field center. This combination of parameters produces the best compromise for imaging sensitivity and quality possible with the current VLA correlator, which dates from the 1970s. The finite bandwidth of the spectral channels still produces some radial smearing of the image away from the field center which we take into account in the analysis of the image.

2.1. Calibration, Editing, and Imaging

For calibration, editing, and imaging a procedure similar to that described in Paper I was used. The Baars flux density
scale (Baars et al. 1977) was adopted using 3C286 as the flux calibrator. Two of the 15 channels in each IF were deleted due to interference which is generated by the VLA itself and which should disappear when the EVLA is completed. Unless otherwise stated, the AIPS package (Greisen 2003) was used to reduce these data.

A faceted, low-resolution image (90′′ clean beam) with a radius of 15′′ was made to find interfering sources far from the area of interest. Facets centered on all very bright NVSS sources (> 30 Jy) out to 100′′ from the field center were also included in this exploratory image. From this search 288 facets, each with 500 × 500 pixels, were chosen to cover a central region 93′′ in radius and all the other bright sources found in the low-resolution search. The facets were defined using the task SETFC which creates a set of overlapping circular regions within the square facets to cover the entire desired field. Then IMAGR was used to deconvolve all the facets together, using the standard Cotton–Schwab–Clark clean algorithm (Schwab 1984). The cell size for the final image is 2′′ and the clean beam size is 6′37′′ × 5′90 pa = 86′′.

Clean images from the first day of the observations were then used as fiducial models for each of the other days. Phase and amplitude calibrations were made of each of the other days using the clean components from the first day images. The A configuration data for each IF and polarization were then combined into a smaller, averaged data set using STUFFR and images for the full data sets were made. The C configuration data were also calibrated using the full A configuration images. The A and C data sets were then combined using DBCON and images were made separately for each IF and polarization.

After making these images there remained some significant residual structures in the central 2′ of the image due to bright sources located outside the central region. These residuals are likely due to (1) differences in the primary beam patterns from antenna to antenna due to the very simple dipole feeds used on the VLA, and (2) the rotation with parallactic angle of the sensitivity pattern on the sky during the synthesis. For bright sources in the outskirts of the field, these variations in sensitivity produce local gain variations which are not taken into account in the imaging and self-calibration process. In order to deal with this type of error, an AIPS procedure, PEELR, was developed and made generally available in the AIPS package. In PEELR the best clean model is subtracted from the self-calibrated $uv$ data, except for the facet containing the bright source responsible for the residuals. These mostly residual data are then self-calibrated as a function of time using only the model for the bright source. This process allows the variations in gain due to the actual primary beam of each antenna to be tracked in time. This local complex calibration is then applied to the mostly residual data and the model for the bright source subtracted from the locally calibrated result. This operation removes, as accurately as possible, the contribution of the offending source. The inverse of the local calibration is applied to the resulting fully residual data and the full clean model added back to the $uv$ database. If there are several offending sources, this process can be repeated for each source as it was in the present case. When the “peeled” data set is then imaged, the effects of the offending outlying sources are significantly reduced. Techniques like this one have been used by others, but only by combining several different steps and perhaps not quite in the same way as described here.

The resulting images still showed radial smearing for bright sources in excess of what is expected from the finite bandwidths. To explore these errors we subtracted the clean component model from each visibility data set and made spectral line image cubes from the residual visibilities. For facets containing bright sources far from the field center, these images showed frequency-dependent artifacts which are likely due to the different slopes of the bandpass across each spectral channel. This instrumental problem causes the effective observing frequency for each channel to be slightly different than is assumed and thus the $uvw$ coordinate for each channel used in the imaging to be slightly in error. As a consequence, the source image in each channel is slightly mis-registered, producing a radial smearing for very bright sources far from the field center. To remove the error pattern due to this effect we cleaned the spectral residual image cubes in facets containing bright, outlying sources and subtracted the resulting clean components from the corresponding visibility data. This reduced the error pattern significantly.

The resulting four sets of 288 facets were then made into single images using FLATN. Finally a weighted average of the four images was made, weighting by the $1/rms^2$, as determined from the IMEAN fit to the pixel histogram. This final image still showed a weak, large-scale error pattern due to the imperfections of the corrections described above. For the final image used for most of the analysis, the AIPS program MWFLT was used to calculate the “mode” of the image over an 82′′ × 82′′ support window and the result was subtracted from the image. For sources approaching this scale size the image before MWFLT was used for analysis but for the vast majority of the sources the MWFLT image was used.

The rms noise near the center of the final image is ~70 μ Jy beam$^{-1}$ making it one of the most sensitive surveys to date made at such a long wavelength. The corresponding value for the 20 cm image discussed in Paper I is much lower, ~ 2.7 μ Jy beam$^{-1}$. For a spectral index, $\alpha_{20}$ ~ 0.7 the ratio of flux densities between 90 cm and 20 cm is ~ 2.8. Thus the effective sensitivity difference in the field center is about one order of magnitude. However, the resolution for the full sensitivity image is about 4′× worse at 90 cm than at 20 cm. Also the primary beam at 90 cm is about 4′× wider. Since many of the sources are resolved at 20 cm and because most are more than a few arcminutes from the field center, the sensitivity difference is not as large as at the field center and can be better at 90 cm than at 20 cm very far from the field center. Thus in comparing the two surveys we need to keep in mind the local properties of each source in the image of interest at each wavelength.

### 2.2. Cataloging

Although the primary beam has a diameter of 2:3 and the region we imaged extends out far beyond this limit, we chose to catalog the region within 1° of the field center. This 2′ diameter field-of-view covers more than the entire field we are studying at other wavelengths. Moreover, the primary beam shape becomes less well known beyond 1° and the smearing due to the finite channel width begins to become important beyond this radius. As with the 20 cm survey we include the radial smearing due to the finite bandwidth in our Gaussian fits. In the present case, the angular FWHM of the radial smearing function is approximately

| Configuration | Start Date | End Date | Hours |
|---------------|------------|----------|-------|
| A             | 2006 Feb 19| 2006 May 17 | 77.1  |
| C             | 2007 Jan 4 | 2007 Jan 5  | 7.9   |
0.0012 times (the distance from the field center). In the worst case, for a point source at the maximum cataloged radius from the field center, this bandwidth smearing amounts to a decrease in the peak brightness at full resolution of ~ 18%. As for the 20 cm survey, we convolved our ~ 6" images to resolutions of 12" and 24" to increase the detection sensitivity for large sources. This exercise was much less important than it was for the 20 cm survey, but it did yield higher S/N detections for a subset of the survey.

As for the 20 cm survey, the AIPS program SAD was used for forming the initial source lists. A catalog for each resolution was formed down to a peak signal/noise (S/N) of 4.5. The residual images from SAD were then searched to find any remaining sources missed by the program with an S/N greater than 5.0. For sources with an S/N close to 5.0, the fitting process was repeated by hand with JMFIT, using the local rms estimate over a region 100 pixels in diameter. In this way, a reliable list of sources with S/N of 5.0 or greater at each resolution was compiled. For both SAD and JMFIT, the smearing due to the finite bandwidth was included in the fitting process. As described for the 20 cm survey in Paper I, the best description of each of the sources with a peak S/N ≥ 5 at one of the resolutions analyzed was included in the full 90 cm catalog. In order to allow for a variety of potential calibration errors, a 3% error term proportional to the total measured flux density of each source was folded into the errors in quadrature, as was done for the 20 cm survey.

3. RESULTS

3.1. Radio Catalog

In Table 2, we give the first ten lines of the radio catalog; the full table is provided electronically. Column (1) contains the source number. If the source has a number less than 3000, then it was found with an S/N ≥ 5.0 from running SAD on the full resolution image. Sources with numbers ≥ 10000 were found in lower resolution images or in checks of the residual images. Numbers beginning with 12 were measured on a 12" resolution image. If the number begins with 24 then we used a 24" resolution image. The lower resolution fits were used in the table when they indicated a significantly larger total flux density for the source in question. Each of these cases was also investigated by eye to confirm the result. Columns (2) and (3) contain the radio R.A. and decl. along with the estimated error. Column (4) contains the corrected peak flux density from the map in μJy per beam. In Column (5) we list the corrected total flux density for the source in question. Each of these cases was also investigated by eye to confirm the result. Columns (2) and (3) contain the radio R.A. and decl. along with the estimated error. Column (4) contains the corrected peak flux density from the map in μJy per beam. In Column (5) we list the corrected total flux density with different properties in angular size and absolute flux density. In Column (6) we give the estimated error in the total flux density. Column (7) contains the peak S/N. The error for Column (4) can be recovered by dividing Column (4) by Column (7). We give the S/N as opposed to the error since the S/N was used to define the catalog cutoff and later is used in the calculation of log N−log S. In Column (8), we give the best-fit deconvolved size in arcseconds. If a resolved two-dimensional Gaussian was the best fit, we give the major and minor axis size (FWHM) and the position angle. Upper limits are given for sources which were unresolved based on the results of JMFIT or SAD. When the minor axis is unresolved, we give “0” as the minor axis size in the table and assume a one-dimensional Gaussian size when estimating the total flux density. Sources with very large sizes, for which only a largest angular size is given in Column (8), sizes and total flux densities were estimated directly from the images using the AIPS routines, IMVAL, and TVSTAT.

3.2. Angular Size Distribution

The 90 cm catalog covers a larger area than the 20 cm survey but at a significantly lower sensitivity. This means that the 90 cm survey samples sources in a higher range in 20 cm flux density.
Figure 2. Observed median angular size for various different logarithmic ranges in 90 cm flux density. Blue dots show significant detections of the median, while the red triangles are upper limits to the median. The error bars in the flux densities show the size of the bins used to calculate the statistics, while the error bars in the sizes are estimated errors in the median values.

Table 3
90 cm Source Size Statistics

| log(S_{90})^a | Num^b | Size^c | log(S_{90})^d |
|--------------|-------|--------|---------------|
| 5.0–6.1      | 20    | 17.0(7.9)| 5.25         |
| 4.0–5.0      | 95    | 7.0(4.5)| 4.41         |
| 3.5–4.0      | 126   | 4.5(2.7)| 3.71         |
| 3.0–3.5      | 335   | < 4    | 3.18         |
| 2.5–3.0      | 859   | < 5    | 2.76         |

Notes.
a Range of the log of 90 cm flux densities with S_{90} in μJy.
b Number of sources in interval.
c Median size with error in median in parenthesis.
d Median of the 90 cm flux density of the subsample in μJy.

radio luminosity than our 20 cm survey. In Figure 1 we show the median angular size ~90 cm flux density distribution. Above 3 mJy we resolve most of the sources but below 3 mJy most of the sources are relatively small. Our 20 cm results for the same sources reported in Paper I show that the typical median size is ~1′\'. This trend in the measured median sizes at 90 cm is shown in Table 3 and Figure 2. Although similar resolution data have not been reported at 90 cm these results are also consistent with previous results at higher frequencies, extrapolated to 90 cm (Windhorst 2003).

Some of the 90 cm sources have larger sizes than the corresponding 20 cm counterparts. For these sources we checked the flux densities and sizes at 20 cm by smoothing to the resolution of the 90 cm detection images. For most of these sources the lower resolution 20 cm sizes and flux densities agree well with the fits at the original resolution. The total flux density changed by more than 10% for only three individually cataloged 20 cm sources (00061, 01186, and 01193). In making the 20 cm catalog, the larger flux densities at lower resolution were rejected because the S/N was significantly higher on higher resolution images which fitted smaller sizes. The 90 cm survey is also more sensitive to smaller spatial frequencies and any steeper spectrum, more extended emission. While these results do not change any of the conclusions in Paper I, we are likely a little incomplete for the largest sources at 20 cm, especially near the bottom of the catalog. For the spectral index analysis below we have used the 20 cm fits from imaging at 90 cm resolution.

### 3.3. Spectral Indices

#### 3.3.1. 90 cm Selected Sources

For our spectral index analysis we restrict ourselves to sources within 20′ of the field center. At that radius we are complete at 20 cm and beyond that distance from the field center the uncertainty due to the primary beam correction at 20 cm becomes significant. Since the 20 cm image is so deep, almost all the 90 cm sources within 20′ of the field center have counterparts which we can use to determine spectral indices. Two 90 cm sources (01492 and 01501) were detected on the 20 cm 6′ resolution image only with S/N < 5. Three more sources (00766 and 01346) have no counterparts on our deep 50 cm GMRT image (F. N. Owen et al. 2009, in preparation) or our deep 50 cm GMRT image (V. Strazzullo et al. 2009, in preparation) and the total 20 cm flux density were used to calculate the spectral index.

Table 4
Spectral Indices for 90 cm Selected Sources

| Name | α_{90,20}^a | Error | S_{90} | S_{20} | Res^b | Size | Res^b | Size | Note^c |
|------|-------------|-------|--------|--------|-------|------|-------|------|-------|
| 00725| 0.57        | 0.07  | 758    | 330.2  | < 4   | r    | 7     | < 2.4| *     |
| 00727| 0.48        | 0.11  | 813    | 211.4  | r     | 7    | <     | 2.4  |       |
| 00728| -0.40       | 0.04  | 2166   | 2906.2 | r     | 3    | r     | 1.5  |       |
| 00733| 0.29        | 0.04  | 1219   | 803.6  | < 1   | r    | 0.8   |      |       |
| 00737| 0.48        | 0.04  | 3000   | 1487.5 | r     | 2    | r     | 2.0  |       |
| 12407| 0.90        | 0.06  | 1211   | 272.4  | r     | 12   | r     | 7.0  | *     |
| 00744| 0.72        | 0.12  | 390    | 136.3  | < 6   | r    | 2.8   |      |       |
| 00755| 0.46        | 0.06  | 2090   | 1069.1 | r     | 9    | r     | 8.3  |       |
| 00756| 0.86        | 0.12  | 402    | 114.4  | < 5   | r    | < 2.4|       |       |
| 00761| 0.33        | 0.09  | 512    | 314.3  | < 3   | r    | 1.3   |      |       |

Notes.
a 90 cm-20 cm spectral index, S ∝ ν^{-α}.
b “<”: next column upper limit, “r”: next column deconvolved major axis.
c α: Spectral index determined from peak of equal resolution images at 20 cm and 90 cm.
Figure 3. Histogram of 90 cm to 20 cm spectral indices for sources detected above 5σ at 90 cm in the region cataloged for the 20 cm survey.

Table 5
Spectral Index Summary for 90 cm Selected Sources

| log(S_90) | Num | α | std | log(S_90) mean | log(S_90) med |
|----------|-----|----|-----|---------------|--------------|
| All      | 278 | 0.69(0.02) | 0.70(0.03) | 0.31 | 3.38 | 2.77 |
| 2.5–5.0  | 229 | 0.68(0.02) | 0.70(0.03) | 0.31 | 3.38 | 2.77 |
| 4.0–5.0  | 11  | 0.70(0.05) | 0.66(0.07) | 0.17 | 4.48 | 4.37 |
| 3.0–4.0  | 56  | 0.68(0.04) | 0.76(0.06) | 0.34 | 3.37 | 3.23 |
| 2.5–3.0  | 162 | 0.68(0.02) | 0.70(0.03) | 0.30 | 2.72 | 2.67 |
| > 3″      | 25  | 0.71(0.03) | 0.72(0.04) | 0.21 | 3.68 | 3.02 |
| 4.0–5.0  | 7   | 0.75(0.08) | 0.77(0.10) | 0.19 | 4.43 | 4.24 |
| 3.0–4.0  | 22  | 0.74(0.05) | 0.76(0.07) | 0.24 | 3.40 | 3.25 |
| 2.5–3.0  | 26  | 0.68(0.04) | 0.67(0.05) | 0.19 | 2.77 | 2.76 |
| ≤ 3″     | 25  | 0.67(0.03) | 0.70(0.03) | 0.34 | 3.22 | 2.70 |
| 4.0–5.0  | 4   | 0.60(0.04) | 0.61(0.05) | 0.06 | 4.54 | 4.49 |
| 3.0–4.0  | 34  | 0.65(0.07) | 0.67(0.08) | 0.38 | 3.37 | 3.23 |
| 2.5–3.0  | 136 | 0.68(0.03) | 0.71(0.04) | 0.19 | 2.77 | 2.77 |

Notes.  
* Range of the log of 90 cm flux densities with S_90 in μJy.  
* Number of Sources in the interval.  
* Spectral Index between 90 cm and 20 cm defined as S ∝ ν^{-α}.  
* Estimated standard deviation in the population.  
* μJy.  
* The log of the mean or median of each subsample is given in this column.

Table 6
Spectral Indices for 20 cm Selected Sources

| Name | α_{90}^{20} | α_{20}^{90} | Error | S_{20} | S_{90} |
|------|-------------|-------------|-------|--------|--------|
| 00013 | 0.57 | 0.70 | 0.007 |
| 00016 | −0.40 | 0.04 | 0.004 |
| 00021 | 1.02 | 0.06 | 0.06 |
| 00024 | 0.58 | 0.18 | 0.10 |
| 00028 | 0.86 | 0.12 | 0.09 |
| 00029 | 0.33 | 0.10 | 0.09 |
| 00030 | 0.82 | 0.10 | 0.09 |
| 00033 | <0.28 | <0.12 | 0.10 |
| 00037 | <−0.12 | 0.10 |

Note. 4 90 cm–20 cm spectral index, S ∝ ν^{-α}.

Most recent work on deep fields involves surveys at 20 cm, so it is also interesting to study the spectral index distribution when selecting the sources at 20 cm. Since most of the 20 cm sources are not detected directly at 90 cm, we must use a combination of a high 20 cm flux density cutoff to study the stronger 20 cm sources individually and stacking subsets at 90 cm in order to study the fainter 20 cm population. Most of the weaker sources are much smaller than the size of the synthesized beam of our 90 cm survey (see Paper I). Those sources that are expected to be unresolved at 90 cm are suitable for stacking analysis.

For the high flux density subset, we select only 20 cm sources with total flux densities > 100 μJy from Paper I within 20′ of the field center. In Table 6 we show the first 10 lines of the electronic table of the 90 cm–20 cm spectral indices for these sources. In Figure 4 we plot the histogram of the spectral indices of these sources against their 20 cm flux densities. Since, in this subset of sources, many of the sources are not detected above 3σ at 90 cm, we plot the blue area for sources detected above 3σ while the red area represents the 3σ upper limit corrected for the observed 20 cm source size. The median spectral index is 0.52(0.04) including the upper limits, significantly flatter than the 90 cm selected sample and samples with brighter limiting flux densities selected at 20 cm. In Figure 5 we show spectral index plotted against the 20 cm flux density for sources with S_{20} > 100 μJy. This plot shows the sources with 90 cm upper limits as red circles clearly delineating the section of the plot which is not allowed due to the 90 cm sensitivity. Even with this high limit on the 20 cm catalog, 37% of the sources with 100 μJy < S_{20} < 1000 μJy have upper limits at 90 cm; thus we cannot determine the details of the dependence of the spectral (Benn et al. 1982). We have only a few sources with 90 cm flux densities > 40 mJy in our 90 cm survey, so our results are consistent with a flattening in the mean spectral index below the 5C12 characteristic flux density. The deeper LBDS 327 MHz survey has a 90 cm selected, 327–1462 MHz median spectral index shifting from ~ 0.9 above 100 mJy, to ~ 0.7 between 10 and 100 mJy, and then down to ~ 0.5 between 3.6 and 10 mJy (Oort et al. 1988). We agree with their estimate in the 10–100 mJy range but do not find the flatter median spectral index below 10 mJy near the bottom of the LBDS survey.

3.3.2. 20 cm Selected Sources

Most recent work on deep fields involves surveys at 20 cm, so it is also interesting to study the spectral index distribution when selecting the sources at 20 cm. Since most of the 20 cm sources are not detected directly at 90 cm, we must use a combination of a high 20 cm flux density cutoff to study the stronger 20 cm sources individually and stacking subsets at 90 cm in order to study the fainter 20 cm population. Most of the weaker sources are much smaller than the size of the synthesized beam of our 90 cm survey (see Paper I). Those sources that are expected to be unresolved at 90 cm are suitable for stacking analysis.

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index distribution on 20 cm flux density for $S_{20} < 1$ mJy from the properties of individual sources.

In order to study the spectral index distribution down to the bottom of the 20 cm catalog, we need to use stacking on the 90 cm image. Since we need to restrict the stacks to angular sizes which are effectively unresolved, we omit a modest, but significant number of sources that are resolved by the 90 cm synthesized beam. In the following discussion, we divide the sources into subsets by ranges of 20 cm flux density and also split the subsets into sources which are $> 3\sigma$ and $\leq 3\sigma$. In Paper I we found that sources with $S_{20} < 1$ mJy have a median size of $\sim 1''$, unlike the stronger sources individually detected at 90 cm. If we omit from the stacking analysis the $\sim 10\%$ of sources with $S_{20} < 1$ mJy that have sizes $> 3\sigma$ we expect that the spectral properties of the $\leq 3\sigma$ subsets should be close to those of the full population. In stacking each subsample with flux densities at 20 cm $< 1$ mJy, we extract the observed 90 cm brightness in $\mu$Jy beam$^{-1}$ at the position of the 20 cm source. For small sources this should be a good estimate of the total flux density in $\mu$Jy. Within the subset, we then calculate the mean and median flux densities at both frequencies. The spectral index computed from the two mean flux densities and that computed from the two median flux densities are listed for each subset in the bottom six lines of Table 7. The errors in Table 7 are calculated assuming counting statistics from the total number in each subset, combined in quadrature with an assumed standard deviation for the population of spectral indices of 0.30 which seems appropriate based on the higher flux density, 90 cm selected, spectral indices but is only an educated guess.

For sources stronger than 1 mJy at 20 cm, all except one have a detection at 90 cm. Excluding this source we can calculate the median and mean spectral index for subsets selected by source flux density and size and these are listed in Table 7. In Figure 6 we summarize the results graphically. Above 1 mJy, where we can study both size subsets, the more resolved sources have steeper spectra than the $\leq 3\sigma$ subset. The mean and median spectral indices continue to flatten for the full population. For the small sources, the median and mean spectral indices flatten to $\sim 0.3-0.5$. Below 1 mJy the small source medians and means continue to be in the range $\sim 0.3-0.5$, but with a clear trend to steeper spectra at the lowest flux densities in the 20 cm sample.

**Figure 4.** Histogram of 90 cm to 20 cm spectral indices for sources with 20 cm flux densities $> 100$ $\mu$Jy. Blue: measured spectral indices for 90 cm sources with $S_{90}/N > 3$, Red: $3\sigma$ upper limits for 90 cm sources with $S_{90}/N < 3$.

**Figure 5.** 90 cm to 20 cm spectral indices vs. 20 cm flux density plotted on a logarithmic scale. Blue dots are sources with 90 cm detections $> 3\sigma$. Red dots are sources with $3\sigma$ 90 cm upper limits.

**Table 7**

| log($S_{20}$)$^a$ | Num$^b$ | $\sigma^2$ | $\alpha^c$ | $\sigma^d$ | log($S_{90}$)$^e$ | log($S_{90}$)$^f$ |
|------------------|--------|------------|------------|------------|------------------|------------------|
|                  |        | mean | med | mean | med | mean | med |
| All              |        |      |    |      |     |      |     |
| 2.5–3.0          | 43     | 0.54(0.06) | 0.54(0.06) | 3.73 | 3.40 |
| 3.0–5.0          | 24     | 0.66(0.11) | 0.66(0.11) | 4.21 | 4.16 |
| 4.0–5.0          | 5      | 0.66(0.19) | 0.66(0.19) | 4.22 | 4.14 |
| 3.0–4.0          | 19     | 0.66(0.27) | 0.66(0.27) | 4.22 | 4.15 |
| $> 3\sigma$      |        |      |    |      |     |      |     |
| 3.0–5.0          | 12     | 0.76(0.12) | 0.76(0.12) | 3.71 | 3.57 |
| 4.0–5.0          | 2      | 0.93(0.36) | 0.93(0.36) | 4.19 | 4.19 |
| 3.0–4.0          | 10     | 0.74(0.14) | 0.74(0.14) | 3.49 | 3.44 |
| $\leq 3\sigma$   |        |      |    |      |     |      |     |
| 3.0–5.0          | 12     | 0.60(0.17) | 0.60(0.17) | 3.75 | 3.35 |
| 4.0–5.0          | 3      | 0.57(0.19) | 0.57(0.19) | 4.19 | 4.16 |
| 3.0–4.0          | 9      | 0.59(0.22) | 0.59(0.22) | 3.28 | 3.29 |
| 2.5–3.0          | 28     | 0.30(0.09) | 0.30(0.09) | 2.69 | 2.70 |
| 2.3–2.5          | 35     | 0.37(0.08) | 0.37(0.08) | 2.41 | 2.41 |
| 2.1–2.3          | 87     | 0.45(0.06) | 0.45(0.06) | 2.20 | 2.20 |
| 1.9–2.1          | 180    | 0.50(0.05) | 0.50(0.05) | 2.00 | 2.00 |
| 1.6–1.9          | 485    | 0.52(0.05) | 0.52(0.05) | 1.74 | 1.74 |
| 1.0–1.6          | 479    | 0.52(0.05) | 0.52(0.05) | 1.46 | 1.46 |

**Notes.**

$^a$ Range of the log of 20 cm flux densities in the interval with $S_{20}$ in $\mu$Jy.

$^b$ Number of Sources in the interval.

$^c$ Spectral Index between 90c and 20 cm defined as $S_{20}/S_{90}$.

$^d$ $\mu$Jy.

$^e$ The log of the mean or median of each subsample is given in this column.

3.3.3. 90 cm versus 20 cm Selection

The results for the spectral indices are quite different depending on whether we select the samples at 90 cm or 20 cm. At 90 cm we find very constant mean and median spectral index of $\sim 0.7$ down to the survey limit of 300 $\mu$Jy. No obvious dependence is found on angular size. Approximately the same result is found in the 90 cm selected sample down to 1 mJy at 20 cm which would correspond to $\sim 3$ mJy at 90 cm with a spectral index $\sim 0.7$. However, sources $> 3\sigma$ in size tend to have steeper spectra than those $\leq 3\sigma$. Below 1 mJy at 20 cm, many more sources do not have detections than would be expected if the $\sim 0.7$ spectral index continued. For these and weaker...
sources, we are forced to consider only small sources since the surface brightness sensitivity at 90 cm is not high enough to detect sources of all angular sizes. For this population of small sources, we find much flatter median and mean spectral indices, $\sim 0.3–0.5$. This result suggests that there is a smaller size, 20 cm source population which is attenuated enough at 90 cm, relative to an $\alpha_{20} \sim 0.7$, to affect the median source properties relative to a 90 cm selected population.

### 3.4. Log $N$–Log $S$

The calculation of the 90 cm log $N$–log $S$ is much easier than for 20 cm in Paper I because (1) we only consider a radius of $1^\circ$ which does not reach the half power point of the primary beam, (2) the synthesized beam is bigger, $\sim 6^\prime 2$, so fewer sources are resolved, and (3) the fractional channel bandwidth is smaller. The these parameters dramatically reduce the problems we faced in Paper I and allow us to perform a simpler analysis. Only below 1 mJy is the incompleteness due to source size an issue. For weak sources we use the same formalism as in Paper I to account for missing sources due to resolution and bandwidth smearing and the same assumed source size distribution. Even for the weaker sources, since the resolution is lower, the impact of these corrections is very small. In Table 8, we summarize our results for the 5σ catalog only, unlike Paper I where we performed a more complicated calculation with a variable S/N cutoff.

In Figure 7, we plot our results along with the 327 MHz results for LBDS (Oort et al. 1988) for their 5σ catalog and the 5C12 results from 408 MHz scaled by their quoted mean spectral index of 0.9–324.5 MHz (Benn et al. 1982). The results are in general agreement and our additions show that we have reached the flat region of the counts seen at other frequencies near 3 mJy. This change in slope also corresponds roughly to the minimum in the spectral index distribution seen in Figure 6.

| $S_1$    | $S_2$    | $S^{2.5}dN/dS$ |
|----------|----------|-----------------|
| S1 μJy   | S2 μJy   | S1 Jy sr$^{-1}$ |
| 375      | 475      | 25.4 ± 3.7      |
| 475      | 600      | 25.9 ± 3.7      |
| 600      | 900      | 16.9 ± 1.8      |
| 900      | 1350     | 17.2 ± 2.4      |
| 1350     | 2000     | 19.3 ± 2.0      |
| 2000     | 3000     | 27.3 ± 2.9      |
| 3000     | 4500     | 30.8 ± 4.2      |
| 4500     | 6750     | 58.0 ± 7.9      |
| 6750     | 10000    | 48.7 ± 9.4      |
| 10000    | 20000    | 89.0 ± 14.7     |
| 20000    | 40000    | 243.6 ± 43.7    |
| 40000    | 80000    | 495.6 ± 105.1   |
| 80000    | 160000   | 398.1 ± 162.5   |

**Notes.** The table contains (1) $S_1$ (the lower flux density limit of the bin), (2) $S_2$ (the upper flux density limit if the bin), (3) the normalization factor and its error.

### 4. DISCUSSION

These data fill out the picture of the meter-wavelength radio sky a bit more clearly, building on the earlier work cited above, but also raise new questions. Instead of finding a large steep spectrum population, we find flatter spectra for the subset of sources. Instead of finding a large steep spectrum population, we find flatter spectra for the subset of sources with angular sizes $< 3^\prime$ and $S_{20} < 10$ mJy. We also find that the differential log $N$–log $S$ at 90 cm flattens in roughly the same flux density range ($S_{90} < 5$ mJy). Thus the nature of the meter wavelength population seems to be changing in the few mJy range. Often a trend toward flattening radio spectra at higher frequencies and the corresponding change in slope of log $N$–log $S$ is attributed to star-forming galaxies becoming dominant (e.g., Windhorst 2003). However, only for 20 cm luminosities $< 10^{23}$ W Hz$^{-1}$ are star-forming galaxies more common than AGN (e.g., Condon et al. 2002). For sources with $S_{20} > 1$ mJy (equivalent to $S_{90} > 2$ mJy with $\alpha_{20} \sim 0.5$) to have a 20 cm luminosity $< 10^{23}$ W Hz$^{-1}$, their redshift would have to be $< 0.2$. This redshift is much too low for most such mJy sources.
to be dominated by star-formation, since we find a median $z \sim 1$ for our sample (V. Strazzullo et al. 2009, in preparation). Thus it seems likely that the changes we are observing are in the AGN population. Furthermore, spectral studies at wavelengths $<20$ cm, show that the typical $\mu$Jy source has a quite steep spectrum, $\sim0.8$–0.9 (Fomalont et al. 2006). Therefore our 20 cm selected $\mu$Jy sources with flatter spectra cannot be due to free–free emission, since the flat spectrum free–free emission should be less important at longer wavelengths.

One might think that flatter spectra in AGNs might be due to synchrotron self-absorption as is seen in many beamed radio galaxies and quasars. However, our work in Paper I and other studies (e.g., Muxlow et al. 2005; Fomalont et al. 2006) show that the typical sizes for these sources are $\sim1''$. This argues against synchrotron self-absorption being dominant since that mechanism requires sizes $\ll1$ mas to be important. One possibility is that the synchrotron spectrum could result from the combination of a relatively flat-spectrum AGN jet with a spectral index $\sim0.5$ (e.g., Bridle & Perley 1984; Butcher et al. 1980) and a synchrotron self-absorbed core.

Since the sources are relatively small, free–free absorption is a possibility. Free–free absorption for such sources depends in general on the details of the clumpiness of the absorbing thermal gas and its geometric relation to the synchrotron emitting medium. In star-forming systems which have been well studied, the radio emission is extended more uniformly throughout the galaxy than the dust or the $\text{H} \text{II}$ regions (Hoernes et al. 1998; Murphy et al. 2008). Free–free absorption is also seen on small scales in some radio AGNs (e.g., Walker et al. 1994; Gallimore et al. 2004). For a uniform density foreground medium with a temperature $\sim10^4$ K, the characteristic free–free absorption turnover frequency is $\nu_t(\text{MHz})\sim0.5n(\text{cm}^{-3})\sqrt{I}(\text{pc})$, where $I$ is the projected pathlength. For example, for a typical source in our sample with a size of $1''$ at $z\sim1$, a typical radius is $\sim4$ kpc and, for a rest-frame turnover frequency of $\sim300$ MHz, one needs a density of $10^4$ cm$^{-3}$, which would correspond to a mass of $\sim6\times10^{10}M_\odot$ if uniformly distributed in a sphere. A more realistic model with a smaller filling factor and a different geometry reduces the mass estimates but if free–free absorption is important then a reasonably large mass of ionized gas must be involved. The flattening could also be due to ionization losses as has been suggested for some star-forming galaxies (e.g., Thompson et al. 2006). In any case, the flatter spectra and the flatter counts observed below 3 mJy suggest a change in the nature of the population below this flux density level which is not well understood. We will discuss this point further in future papers where we add redshifts and data from other wavelengths to the analysis.

5. CONCLUSION

We have presented a very sensitive 90 cm image of the SWIRE deep field. This image, combined with our uniquely sensitive 20 cm image of this field, allows us to study the meter wavelength spectral indices as a function of flux density for the $\mu$Jy radio population. For 90 cm selected sources the properties of the sources are consistent with previous work with a mean spectral index near 0.7 and few very steep spectrum sources. Thus no large population of very steep spectrum $\mu$Jy sources seems to exist down to our limiting flux density.

For the subset of sources selected at 20 cm with sizes $<3''$ (which contains about $\sim90\%$ of all 20 cm selected sources $<1$ mJy), the mean and median spectral indices flatten from $\alpha\sim0.7$ to $\alpha\sim0.3$–0.5 below 10 mJy with a trend toward steeper spectra at the lowest flux densities. The 90 cm log $N$–log $S$ counts flatten below 5 mJy as they do at corresponding low flux densities at higher frequencies. The change in the source properties at a few mJy is not well understood but probably involves the AGN population, not primarily star-formation-dominated galaxies.

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