MIPS 24 μm OBSERVATIONS OF THE HUBBLE DEEP FIELD SOUTH: PROBING THE IR–RADIO CORRELATION OF GALAXIES AT z > 1

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ABSTRACT

We present MIPS 24 μm observations of the Hubble Deep Field South taken with the Spitzer Space Telescope. The resulting image is 254 arcmin² in size and has a sensitivity ranging between ~12 and ~30 μJy rms, with a median sensitivity of ~20 μJy rms. A total of 495 sources have been cataloged with a signal-to-noise ratio greater than 5σ. The source catalog is presented as well as source counts which have been corrected for completeness and flux boosting. The IR sources are then combined with MUSYC optical/NIR and ATDFH radio observations to obtain redshifts and radio flux densities of the sample. We use the IR/radio flux density ratio (q24) to explore the IR–radio correlation for this IR sample and find q24 = 0.71 ± 0.31 for sources detected in both IR and radio. The results are extended by stacking IR sources not detected in the radio observations and we derive an average q24 for redshift bins between 0 < z < 2.5. We find that the high-redshift (z > 1) sources have an average q24 ratio which is better fit by local LIRG SEDs rather than local ULIRG SEDs, indicating that high-redshift ULIRGs differ in their IR/radio properties. So, ULIRGs at high-redshift have SEDs different from those found locally. Infrared-faint radio sources are examined, and while nine radio sources do not have an MIPS detection and are therefore radio-loud active galactic nuclei (AGNs), only one radio source has an extreme IRAC 3.6 μm to radio flux density ratio indicating it is a radio-loud AGN at z > 1.

Key words: galaxies: evolution – galaxies: formation – galaxies: starburst

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The tight correlation between the far-IR and radio emission of star-forming galaxies has been well studied in the local universe and established over many orders of magnitude in luminosity (e.g., Helou et al. 1985; Yun et al. 2001). The radio emission of normal galaxies is dominated by synchrotron radiation from relativistic electrons accelerated by supernovae and free–free emission from H ii regions (Condon 1992). Both supernovae and H ii regions are related to young, massive stars (M > 10 M⊙), and hence radio emission in normal galaxies is correlated with star formation. The UV emission from young stars is re-radiated by dust in the mid-to-far-infrared so IR emission is also related to star-forming processes. The far-IR/radio correlation is important because it is a probe of the star-forming processes taking place. Deviations from the correlation may occur due to, for example, the varying strength of galactic magnetic fields, evolution of dust and metallicity properties, and increasing inverse Compton losses off the cosmic microwave background (e.g., Murphy 2009; Lacki & Thompson 2010). The far-IR/radio correlation can also be used to select radio loud active galactic nucleus (AGN; e.g., Donley et al. 2005). Thus, it is important to determine whether the correlation holds at high redshift.

A sensitive infrared probe of high-redshift star formation is the 24 μm band of the Multiband Imaging Photometer for Spitzer (MIPS) instrument (Rieke et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004). Several deep surveys have correlated 24 μm with radio data to study the mid-IR/radio relation (Boyle et al. 2007; Beswick et al. 2008; Ibar et al. 2008; Garn & Alexander 2009). Some of these authors (Boyle et al. 2007; Beswick et al. 2008) observe a change in the mid-IR/radio ratio at faint radio and/or 24 μm flux densities, but the differences in the results are likely to be because of selection biases which lead to different populations being studied.

More recent work in the COSMOS field has found little variation in the IR–radio ratio of star-forming galaxies for z < 1.4, and for the limited sample of sources confirmed at z > 2.5 the average IR–radio ratio is still the same as that found locally (Sargent et al. 2010). Discrepant measurements of the average IR–radio ratio can be reconciled by the fact that previous studies selected in either IR or radio, or required a detection in both bands (Sargent et al. 2010).

In 1998, the Hubble Space Telescope (HST) observed a region in the southern continuous viewing zone as a complementary observation to the Hubble Deep Field North (HDF-N; Williams et al. 1996). This field, known as the Hubble Deep Field South (HDF-S; Williams et al. 2000), reaches a limit of ~30 mag in the four HST WFPC2 broadband filters. Simultaneous observations with the other HST instruments, NICMOS and STIS, reach similarly deep levels in the near-infrared and ultraviolet. In addition to the main HST deep fields, a mosaic of nine flanking fields was imaged to shallower levels of ~25 mag in I (F814W) (Lucas et al. 2003). Wide-field ground-based imaging has been performed by Palunas et al. (2000) and the Multiband Survey by Yale-Chile (MUSYC) team (Gawiser et al. 2006), reaching R-band magnitude limits of ~25 and 26, respectively. This field has been the target of deep radio observations reaching ~10 μJy rms at 1.4, 2.5, 5.2, and 8.7 GHz (Huynh et al. 2005, 2007).

Confirming the COSMOS results requires a deep and reasonably wide MIPS field. In this paper, we present the MIPS 24 μm
observations of the HDF-S and take advantage of the enormous amount of multiwavelength data available to study the IR–radio correlation of galaxies detected in this field. We use a stacking technique in the radio to determine the average IR–radio ratio of a flux-limited IR selected galaxy sample.

In Section 1, we describe the MIPS observations and data reduction. We summarize the multiwavelength data used for this work, in particular the MUSYC data, in Section 2. The MIPS source detection and extraction is discussed in Section 4 and here we present the 24 μm catalog, source counts, and redshift distributions. Section 5 reports our work on the IR–radio correlation in the HDF-S and our identification of infrared-faint radio sources (IFRSs) in the field. We conclude with a summary in Section 6. A Hubble constant of 71 km s

2. MIPS OBSERVATIONS AND DATA REDUCTION

The MIPS 24 μm observations of the HDF-S were carried out over two campaigns. The first was in 2004 as part of the guaranteed time observations (GTOs; PI: Fazio) and the second in 2007 Cycle 3 observations (PID 30873, PI: Labbe). The GTO observations were taken using the MIPS photometry mode and covered six pointings in the HDF-S region. The Cycle 3 observations consisted of four pointings which covered the area west of the WFPC2 field (Figure 1). The coverage (Figure 1) is very uneven, with effective on sky integration time per pixel ranging from about 4500 s in the deepest area to 900 s in the shallow regions.

The basic calibrated data (BCDs) were downloaded from the Spitzer Science Center (SSC) archive and were reduced using version 18.1.5 of the MOsaicker and Point source EXtractor (MOPEX) software from the SSC. As recommended, the first frame from each commanded sequence of exposures (i.e., DCENUM = 0) was discarded. Mosaicking the BCDs at this area west of the WFPC2 field (Figure 1). The coverage (Figure 1) is very uneven, with effective on sky integration time per pixel ranging from about 4500 s in the deepest area to 900 s in the shallow regions.

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After flat fielding the BCDs the MOPEX task overlap.pl was used to level the backgrounds. The BCDs were then mosaicked in the usual way with MOPEX using the default pixel scale of 2′.45 pixel

3. MULTIWAVELENGTH ANCILLARY DATA

The field was observed by the main three instruments on the HST in 1998 to depths rivaling that of original HDF in the north (Williams et al. 2000). The HST imaging reaches 10σ AB magnitudes of approximately 27.7 in I band (F814W) (Casertano et al. 2000) in the deepest region. Including the flanking fields, Hubble imaging covers only a small ∼50 arcmin

More recently, the MUSYC observed an approximate 37 × 37 arcmin

Figure 1. Left: the MIPS 24 μm image of the HDF-S region. The green chevron figure marks the area covered by the original HST WFPC2 deep field, the squares to the east and south are the HST STIS and NICMOS deep fields, respectively. Right: the coverage map of the MIPS 24 μm image; white indicates most coverage and black indicates no coverage.

(A color version of this figure is available in the online journal.)
Infrared Array Camera (IRAC) data from Spitzer was also obtained as part of the GTO (PI: Fazio) and 2007 Cycle 3 observations (PID 30873, PI: Labbe). The BCDs from the SSC archive had the usual procedures applied to remove cosmic rays and artifacts, such as column pulldown, muxebleed, and maxstripe (see Marchesini et al. 2009 for details). Individual background-subtracted images were combined into mosaics covering two 10 × 10 arcmin² regions to limiting AB magnitudes (3σ) of 24.5, 24.0, 22.2, and 22.1 at 3.6, 4.5, 5.8, and 8.0 μm, respectively (Marchesini et al. 2009).

Accurate photometric redshifts were determined with EAZY from the MUSYC 14 band optical–IRAC data (Marchesini et al. 2009). EAZY, a template-fitting code similar to HYPERZ (Bolzonella et al. 2000) and BPZ (Benítez 2000), has been found to provide high-quality redshifts over 0 ≤ z ≤ 4 (Brammer et al. 2008), despite the fact that it is not trained on a spectroscopic sample. EAZY has the option of linearly combining templates when fitting sources and provides multiple estimates of the photometric redshift, including zpeak, which is determined from the full probability distribution rather than a straight χ² minimization. In the case where there are two widely separated peaks in the redshift probability function, zpeak selects the peak with the largest integrated probability. In the eCDFS, the MUSYC team achieved photometric redshift accuracies of δz/(1 + z) ∼ 0.008 with EAZY, but this result came from supplementing UBV RiJHK optical imaging, with Spitzer IRAC and 18 medium-band optical images from Subaru (Cardamone et al. 2010). The photometric redshifts from the 14 band optical–IRAC data have an accuracy of δz/(1 + z) = 0.000 ± 0.033 and the fraction of catastrophic outliers is only 4% (Marchesini et al. 2009).

The radio observations of the HDF-S were made between 1998 and 2001 with the Australia Telescope Compact Array using all four available frequency bands. Between 100 and 300 hr of observing at each band yielded images at 1.4, 2.5, 5.2, and 8.7 GHz with maximum sensitivities of ∼10 μJy rms (Huynh et al. 2005, 2007).

4. MIPS IMAGE ANALYSIS

4.1. Source Detection and Extraction

Source detection and extraction were performed using the Astronomical Point Source extraction (APEX) tools in the MOPEX software. First, APEX performs a local background subtraction by taking a median within a box surrounding each pixel. The box size was set to 34 pixels, or ∼14 times the FWHM of the 24 μm point-spread function, and the median calculated after rejecting the 100 highest pixels. APEX detects sources when a pixel cluster has values which are above the noise threshold, but this requires a good estimate of the noise. The MOPEX and APEX software can produce several types of noise images. The “std” noise image produced at the mosaicking stage provides the empirical scatter of each pixel from the repeated observations divided by the square-root of the number of observations. This underestimates the true noise because it does not account for pixel-to-pixel correlated noise or confusion noise. APEX generates an output “noise” image by calculating the noise within a local box, and here we use the same settings as for the background subtraction—34 pixel rectangular box and rejection of 100 outlier pixels. Using an approach similar to Frayer et al. (2009), the “std” and “noise” images are then combined in quadrature with equal weights to obtain a combined uncertainty image for source detection and extraction.

We then checked whether the combined uncertainty image was reasonable by checking this against an independent total noise value. An independent estimate of the total noise in the image was made by measuring the flux density in apertures randomly placed on the image and calculating the standard deviation of the measurements. Two hundred apertures were placed randomly in 60 × 60 pixels regions of a residual image with bright sources removed. The standard deviation of the flux density measurements agreed with the combined uncertainty image to within 50%.

Sources were detected by APEX if they had a peak with a signal-to-noise ratio (S/N) greater than 4 and were fitted using the point-source response function image provided by the SSC. The sources were then included in the final catalog if they had a fitted S/N greater than 5. This relatively high S/N ratio was chosen to minimize the number of spurious detections. Even with this S/N ratio the initial source list (504 total) was visually examined for potential spurious sources such as those in the Airy rings of bright sources. Only nine (∼2%) sources were removed, suggesting that the APEX algorithm is reliable. The final 24 μm catalog contains 495 sources.

The full 5σ catalog is presented in Table 1. A description of the table is as follows.

Column 1: source ID.
Column 2: right ascension in J2000.
Column 3: declination in J2000.
Column 4: 24 μm flux density in μJy.
Column 5: 24 μm flux density uncertainty in μJy. This is the formal error from APEX.
Column 6: S/N of the source.

4.2. Completeness and Flux Boosting

The completeness of the source catalog was estimated by simulations. Monte-Carlo-like simulations were performed by injecting 10,000 sources at random locations onto the map and extracting them using the same technique as adopted for the production of the catalog. While completeness levels vary
significantly across the image as a function of coverage and flux density, we can recover the overall completeness level of the generated catalog by injecting sources over the full image. A single source was injected per simulation, and the input flux density varied from 50 to 3000 \( \mu Jy \) to sample the full range of interest. The completeness as a function of flux density is shown in Figure 2. The completeness rises steeply from about 10% at 100 \( \mu Jy \) to approximately 90% at 250 \( \mu Jy \). The 50% completeness level occurs at approximately 150 \( \mu Jy \).

Source detection algorithms that rely on finding a peak above a local noise background lead to flux boosting. This is because sources that lie on a noise peak have their flux density increased and therefore have a higher probability of being detected, while sources which lie on a noise trough have decreased flux densities and may be excluded altogether. This effect is most pronounced in the faintest flux density bins, i.e., in sources with an S/N close to the limit of the catalog. The degree of flux boosting can be estimated by examining the output to input flux density of the simulations (Figure 2). We find that flux densities are boosted by about 1%–4% for measured flux densities of 100–300 \( \mu Jy \), on average. The flux boosting is negligible for sources with true flux densities brighter than 300 \( \mu Jy \).

The simulations can also be used to gauge the positional accuracy of the catalog by comparing input and output positions. The median of the R.A. and decl. offsets are plotted for various input flux density bins in Figure 3. The positional accuracy can be estimated from the standard deviation in the offsets of each of these bins. We find that at the faintest levels (80 \( \mu Jy \)) the R.A. and decl. uncertainties are approximately 0.8 and 1.3 arcsec, respectively. The positional accuracy is much better than 0.5 arcsec for sources that are 1 mJy and brighter. This is the random component only and does not take into account any systematic offsets in the pointing. Spitzer has an absolute pointing uncertainty of about 1 arcsec.

5. RESULTS

5.1. Source Counts

The source counts were derived from the S/N \( \geq 5 \) catalog. We correct the source counts for flux boosting and completeness using the results of Section 4.2. Figure 4 shows the Euclidean normalized source counts \((dN/dS \times S^{2.5})\) and the results are tabulated in Table 2. The uncertainties listed are derived from Poissonian statistics. The counts from this work span the peak near 0.2–0.3 mJy. We have also plotted the counts from five GTO fields (Papovich et al. 2004), the F1rst Look Survey (FLS) field (Marleau et al. 2004), and the Spitzer Wide-field InfraRed Extragalactic (SWIRE) fields (Shupe et al. 2008) for
comparison. In the fainter bins, HDF-S counts are broadly consistent with that from the previous work, showing the steep decline for $S_{24} < 0.2$ mJy. At brighter flux densities the counts are consistent with the FLS, within the uncertainties, but lower than that from the GTO or SWIRE fields. At $\sim 0.5$ mJy the SWIRE counts are about 40% higher than the F-S and about 20% higher than the FLS or GTO source counts. This illustrates that there is significant field-to-field variation, which Shupe et al. (2008) estimated to be about 10% for sub-mJy flux densities in regions as large as the SWIRE fields ($\sim 7'$).

Also overlaid on Figure 4 are the normalized counts from the model of Lagache et al. (2004). See Lagache et al. (2004) for details; in brief, this model uses starburst and normal galaxy templates and fits for the evolution of the local luminosity function that is best constrained by observed source counts and redshift distributions. We note that this model used counts at 15, 60, 170, and 850 $\mu$m from the literature as well as the 24 $\mu$m counts from Papovich et al. (2004). The model is broadly consistent with the HDF-S, FLS, and GTO counts and reproduces the turnover at $\sim 0.1$ mJy that is seen in these fields.

5.2. Optical Counterparts

We used the MUSYC catalogs to identify optical counterparts to the MIPS sources and obtain redshift information from either the spectroscopic or photometric catalogs. The MUSYC imaging overlaps almost the entire MIPS imaging, with only the $\sim 24$ arcmin$^2$ region north of decl. $= -60.4994$ falling outside the MUSYC observations. Thus, 25/495 (5%) MIPS sources do not have MUSYC coverage. The MUSYC K-selected catalog (Quadri et al. 2007) and v1.0 optical catalog (Gawiser et al. 2006) were searched for counterparts to the rest of the MIPS sample.

With the $\sim 1$ arcsec seeing of the observations and the astrometric uncertainties of the USNO-A2 stars used for astrometry, the positional uncertainties of the MUSYC sources are about 0.2–0.3 arcsec. For MIPS the 1σ positional uncertainty can be estimated by $0.5\theta_{\text{FWHM}} / (S/N)$ assuming Gaussian noise, and hence a beam size of 6 arcsec implies a positional uncertainty of 0.6 arcsec (in each coordinate) for the faintest sources. Including the Spitzer 1 arcsec absolute pointing uncertainty, the 1σ offset between MIPS and MUSYC should be about 1.3 arcsec for the faintest MIPS sources.

Figure 5 shows a plot of distribution of the offsets between all MIPS and MUSYC K-selected (Quadri et al. 2007) sources within 2 arcsec. As expected, there is a peak in the distribution of offsets at $\leq 0.5$ arcsec. The contribution from chance matches due to the optical source density is also shown in Figure 5. We find that the number of chance matches meets the number of observed matches at a radius of $\sim 1.5$ arcsec and therefore use this as our matching radius. Three hundred sixty-nine MIPS sources have a counterpart in the K-selected catalogs and a photometric redshift from Marchesini et al. (2009). A further 37 have counterparts in the optical MUSYC catalogs, which cover a larger area than the K-band imaging. For these 37 sources EAZY photometric redshifts were calculated from the MUSYC UBVRIz optical data plus a narrowband 5000 $\AA$ image. A comparison of these seven-band photometric redshifts with 166 spectroscopic redshifts from the literature finds only 18% have $\delta z / (1 + z) > 0.2$. Excluding these outliers, we find $\delta z / (1 + z) = 0.027 \pm 0.046$, and thus conclude that the photometric redshifts are statistically reliable. In total 406/495 (82%) of the MIPS sources have a MUSYC optical or NIR counterpart. Three have more than one MUSYC source within 1.5 and in these cases the optical candidates were individually examined and the most likely candidate chosen using the $P$ statistic (e.g., Downes et al. 1986; Lilly et al. 1999).

Spectroscopic redshifts from the literature are available for 22 of the MIPS sources, and we assume the photometric redshift, where available, for the remaining sources. The redshift distribution of the MIPS sources peak at $z \sim 0.5$ with a tail to high redshift ($z > 2$; Figure 5). The total infrared luminosity (8–1000 $\mu$m) of the sources is estimated by fitting the 24 $\mu$m flux density to the luminosity-dependent spectral energy distribution (SED) templates of Chary & Elbaz (2001). We integrate the best-fit template over 8–1000 $\mu$m to derive the total IR luminosity (LIR; Figure 6). We find that luminous IR galaxies (LIRGs; $10^{11} L_\odot < \text{LIR} < 10^{12} L_\odot$) are detected out to $z \sim 1.1$, while ultraluminous IR galaxies (ULIRGs; LIR $> 10^{12} L_\odot$) are detected out to higher redshifts. We note that while the Chary & Elbaz (2001) templates exhibit observed FIR flux density ratios which are more representative of $z \sim 1$ galaxies than Dale & Helou (2002) or Lagache et al. (2003) templates (Magnelli et al. 2009), the choice of templates can lead to $\sim 0.3$ dex variation.

### Table 2: The MIPS 24 $\mu$m Source Count for Hubble Deep Field South

| Range in $S_{24\mu m}$ ($\mu Jy$) | Number of Sources ($N$) corrected for incompleteness | $(dN/dS)^{2.5}$ ($\mu Jy^{2.5}$) |
|---------------------------------|-----------------------------------------------------|---------------------------------|
| 110–134 115                     | 24                                                   | 121.4                           | 368.8 ± 75.3                   |
| 134–163 145                     | 65                                                   | 149.4                           | 650.7 ± 80.7                   |
| 163–198 174                     | 70                                                   | 106.8                           | 585.4 ± 70.0                   |
| 198–241 213                     | 83                                                   | 97.5                            | 738.0 ± 81.0                   |
| 241–293 254                     | 70                                                   | 76.0                            | 753.0 ± 90.0                   |
| 293–356 316                     | 54                                                   | 58.0                            | 788.1 ± 107.2                  |
| 356–433 388                     | 37                                                   | 38.4                            | 706.3 ± 116.1                  |
| 433–526 454                     | 29                                                   | 29.7                            | 659.0 ± 122.4                  |
| 526–640 590                     | 13                                                   | 13.2                            | 444.6 ± 123.3                  |
| 640–779 746                     | 14                                                   | 14.3                            | 712.5 ± 190.4                  |

Notes. $N$ is the raw number of galaxies in the bin, and corrected $N$ is the number corrected for incompleteness. The median flux density of the bin, $\langle S_{24\mu m} \rangle$, has been corrected for flux boosting.
in luminosity. Fitting to the 24 μm flux density alone can give a good LIR estimate up to about z ~ 1.4, but for 1.4 < z < 2.5 the LIR can be overestimated by up to a factor of 4 (Murphy et al. 2009).

6. DISCUSSION

6.1. Infrared–Radio Correlation

Radio counterparts to the MIR sources were obtained using the 1.4 GHz radio catalog of the HDF-S (Huynh et al. 2005). We applied a simple radial match of 3 arcsec and find that 84 MIPS sources have a radio counterpart. The matching distance is large enough for obtaining bona fide matches since the 24 μm positional uncertainties are ~1.2 arcsec and the radio positions are better than about 1 arcsec in most cases (Huynh et al. 2005). The P statistic suggests the probability of one or more radio sources within 3 arcsec of an IR one by chance is ~0.3%, but this estimate does not take into account the individual positional uncertainties and assumes the radio source population is not clustered.

The IR/radio correlation as a function of redshift is presented in Figure 7, shown as the observable parameter $q_{24} = \log(S_{24\mu m})/S_{1.4\text{GHz}}$. For the 84 sources with detections in both the IR and radio the median $q_{24} = 0.71 \pm 0.31$. This is consistent with the $q_{24} = 0.84 \pm 0.28$ found in the xFLS Appleton et al. (2004) and $q_{24} = 0.66 \pm 0.39$ in the Subaru XMM-Newton Deep Field (Ibar et al. 2008). Overlaid on Figure 7 are SED tracks from local templates by Chary & Elbaz (2001). We find that up to redshift one the IR sources appear to follow tracks of local SEDs, suggesting the IR–radio correlation holds to this redshift. Above redshift one the 24 μm band starts to observe the MIR regime ($\lesssim 12 \mu m$ rest frame) where polycyclic aromatic hydrocarbon (PAH) emission and silicate absorption strengths vary widely in individual galaxies, and hence a wide range of MIR/radio ratios is possible. The high-redshift (z > 1) sources in Figure 7 also fall within the ratios allowed by local templates, but most are best described by the SEDs of relatively low
luminosity SEDs ($L < 10^{12} L_\odot$). These sources have luminosities that are ULIRG-like ($>10^{12} L_\odot$; Figure 6) but exhibit ratios similar to local $\sim 10^{11}$ LIRGs, implying that the SEDs of high-redshift ULIRGs differ to that of local ones. We speculate that these ULIRGs have strong PAH emission, as seen in other IR samples of high-redshift ULIRGs (e.g., Yan et al. 2007), but IR spectra are needed to confirm this hypothesis.

To extend the results we stack the IR sample in the radio data. First, the IR sources were binned into six redshift bins, as shown in Table 3. For each redshift bin, the radio data were stacked at positions of all undetected sources and a noise-weighted mean image was produced. Stacks of width 60′ were produced and the photometry performed by fitting a point source to the stacked radio image. All stacks, shown as postage stamps in Figure 8, have a significant detection. The resulting $q_{24}$ values from the stacked radio flux densities are shown as blue squares in Figure 7. They have been combined with the actual detections to derive an average $q_{24}$ for all MIPS sources in the various redshift bins (green squares). We find that the average observed $q_{24}$ at high redshift ($z > 1$) is approximately 0.86 (Table 3) and this is consistent with local LIR $\sim 10^{11}$ LIRG SED (Figure 7). At these redshifts our samples have ULIRG luminosities or greater, so this is further evidence that the average IR luminous galaxy at high redshift is better described by a lower luminosity local template. This result is consistent with complementary studies which have found that some high-redshift IR luminous galaxies have cooler SEDs than local galaxies of similar luminosities (Seymour et al. 2010; Muzzin et al. 2010).

As mentioned before, the high-redshift ULIRGs may exhibit stronger PAH emission than local galaxies, leading to a greater $q_{24}$ than expected from local SEDs. However, the increased $q_{24}$ at high redshift may also result from suppressed radio emission. If a galaxy has just begun a burst of star formation then the MIR dust emission may be enhanced due to star formation but the supernova rate, which powers the radio emission, lags the star formation by about $\sim 30$ Myr (the approximate lifetime of 8 $M_\odot$ stars). It is possible that some of the sources at high redshift are nascent starbursts. Increased inverse Compton scattering of the cosmic microwave background at high redshift can lead to lower radio emission than in the local universe, and since the energy density of the CMB scales as $(1+z)^4$ this could be significant at high redshifts. Another potential explanation is that the high-redshift galaxies have lower magnetic field strengths than local galaxies, leading to decreased electron confinement and therefore lower radio emission.

### 6.2. Infrared-faint Radio Sources

IFRSs are a class of radio sources recently discovered in the Australia Telescope Large Area Survey by Norris et al. (2006). These are radio sources brighter than a few hundred $\mu$Jy at 1.4 GHz which have no observable infrared counterpart in the Spitzer Wide-area Infrared Extragalactic Survey (SWIRE; Lonsdale et al. 2004). Most have flux densities of a few hundred $\mu$Jy at 1.4 GHz, but some are as bright as 20 mJy, resulting in extreme infrared to radio ratios. Recent very long baseline interferometry detections have constrained the radio sources sizes to less than 0.03 arcsec, suggesting IFRSs are compact AGNs (Huynh et al. 2010).

Deeper Spitzer legacy survey data in the extended Chandra Deep Field South yielded two IRAC detections of the four IFRSs in that field, and SED modeling of these sources with the new constraints showed that they are consistent with $z > 1$ radio-loud AGNs (Huynh et al. 2010).

The MIPS data of the HDF-S allow us to search for IFRSs in this field. There are nine AT HDFS sources with $S_{1.4 \text{GHz}} > 200 \mu$Jy that do not have an MIPS counterpart. These are listed in Table 4 along with their MIPS ($5\sigma$) limit and IRAC properties. All of these sources have low $q_{24}$ values consistent with radio-loud AGNs, and most have moderate photometric redshifts of $0.417 < z < 1.548$. Most are also relatively bright in the IRAC channels and would have been detected by SWIRE depth IRAC imaging. Of the nine sources, one

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**Table 3**

Summary of Radio Stacking Results of MIPS Sources

| $z$      | Median $z$ | $N_{\text{det}}$ | $N_{\text{stack}}$ | Stacked $S_{1.4 \text{GHz}}$ ($\mu$Jy) | Stacked $q_{24}$ | Average $q_{24}$ | No redshift |
|----------|------------|------------------|---------------------|--------------------------------------|-----------------|-----------------|-------------|
| 0 < $z$ < 0.25 | 0.149     | 8                | 25                  | 15.2 ± 4.1                           | 1.38±0.10       | 1.09±0.06       |             |
| 0.25 < $z$ < 0.50 | 0.389     | 19               | 54                  | 23.8 ± 3.5                           | 1.18±0.06       | 0.93±0.05       |             |
| 0.50 < $z$ < 0.75 | 0.580     | 14               | 65                  | 22.8 ± 5.2                           | 1.05±0.09       | 0.89±0.07       |             |
| 0.75 < $z$ < 1.00 | 0.890     | 3                | 57                  | 16.4 ± 5.0                           | 1.14±0.12       | 1.14±0.10       |             |
| 1.00 < $z$ < 1.50 | 1.270     | 10               | 72                  | 18.2 ± 3.0                           | 1.11±0.07       | 0.86±0.06       |             |
| 1.50 < $z$ < 2.50 | 1.787     | 13               | 61                  | 12.0 ± 2.9                           | 1.27±0.10       | 0.98±0.05       |             |
| No redshift | ...       | 16               | 73                  | 18.7 ± 3.6                           | 1.12±0.08       | 0.89±0.06       |             |

Notes. $N_{\text{det}}$ is the number of MIPS sources in each bin which is detected in the radio image. $N_{\text{stack}}$ is the number of MIPS sources not detected in the radio image and therefore the number stacked in this analysis, resulting in the stacked $S_{1.4 \text{GHz}}$ listed in Column 5. Stacked $q_{24}$ is the IR–radio flux density ratio for the stacked sample. Average $q_{24}$ is the IR–radio flux density ratio for all MIPS sources in the redshift bin, obtained by combining the detections with the stacked results.
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Table 4
Summary of Radio Sources that have No MIPS 24 μm Counterpart and Hence are Candidate Infrared-faint Radio Sources

| Radio ID         | S_{24 μm} limit (5σ, mJy) | S_14GHz (mJy) | q_{24} | S_14GHz/S_3.6 μm | z_{phot} | α_{1.4GHz} |
|------------------|-----------------------------|---------------|--------|------------------|----------|------------|
| ATHDFS_J223224.5−604113 | 130                        | 4.108         | <−1.50 | 37               | 0.746    | −0.48 ± 0.02 |
| ATHDFS_J223245.6−603857  | 100                        | 0.843         | <−0.93 | 27               | 1.548    | −0.69 ± 0.06 |
| ATHDFS_J223230.5−603857  | 70                         | 0.254         | <−0.56 | >127             | 7.0      | −0.80 ± 0.29 |
| ATHDFS_J223350.0−603741  | 80                         | 0.670         | <−0.93 | 4.4              | 0.645    | −0.36 ± 0.05 |
| ATHDFS_J223323.8−603737  | 65                         | 0.645         | <−1.00 | 7.0              | 1.13     | −0.51 ± 0.08 |
| ATHDFS_J223350.5−603503  | 110                        | 1.252         | >4     | <−1.06           | <310     | 0.417      | −0.85 ± 0.05 |
| ATHDFS_J223258.5−603346  | 95                         | 1.010         | <−1.03 | 47.4             | 44       | −0.65 ± 0.05 |
| ATHDFS_J223208.6−603251  | 75                         | 0.821         | <−1.04 | 8.1              | 0.746    | −0.86 ± 0.03 |
| ATHDFS_J223113.5−603147  | 115                        | 0.831         | <−0.86 | ...              | ...      | ...        |

Notes. Only ATHDFS_J223205.9−603857 is faint enough at 3.6 μm to meet the original IFRS definition of Norris et al. (2006). All of these sources have q_{24} values suggestive of radio-loud AGNs. The 3.5 μm data are from Marchesini et al. (2009).

1 Radio spectral indices are from Huynh et al. (2007) and S ∝ ν^{α}.
2 Not detected in MUSYC optical imaging.
3 IRAC image of source has artifacts, so photometry is inaccurate.

7. SUMMARY

We have presented the MIPS 24 μm observations of the HDF-S from the Spitzer Space Telescope. This new MIR image, 250 arcmin<sup>2</sup> in area, reaches a maximum sensitivity of ~12 μJy rms, with the bulk of the image achieving ~20 μJy rms. A catalog of sources brighter than 5σ was compiled, comprising 495 sources. The completeness corrected and flux-deboosted 24 μm source count was presented, and while the counts are consistent with results in the literature they show that there is significant field-to-field variation.

The MIPS sources were matched to MUSYC photometric redshift and ATHDFS 1.4 GHz radio catalogs. The IR–radio ratio q_{24}, log(S_{24 μm}/S_{1.4GHz}), for 84 sources with both IR and radio detections has a median q_{24} = 0.71 ± 0.31, consistent with previous results. We find that while there is diversity in galaxy SEDs, the IR–radio correlation appears to hold out to z ~ 1. The results were extended by splitting the sample into redshift bins and stacking all IR sources not detected in the radio to derive an average radio flux density and hence an average q_{24}. The observed average q_{24} was compared with that expected from local SED templates and at z > 1 the observed average q_{24} is found to be better described by LIRG templates, even though these sources have ULIRG-like luminosities. This is further evidence that the average IR luminous galaxy at high redshift is better described by a lower luminosity local template. The change in q_{24} may be due to enhanced MIR emission, possibly from hot dust heated by AGNs or relatively bright PAH emission, or suppressed radio emission due to lower strength magnetic fields, inverse Compton scattering off the CMB. Several of the high-redshift galaxies may be nascent starburst where the radio emission from supernovae is delayed compared to the IR and hence a high q_{24} results. More detailed IR observations and spectroscopy to determine the AGN/SB nature of the IR galaxies are required to differentiate between these possible scenarios.

The Herschel Space Observatory, launched in 2009 May, is currently undertaking deep IR surveys in bands ranging from 70 to 450 μm. These bands are close to the peak of the IR emission from dust and not significantly affected by AGNs or PAH emission. With its unprecedented depth and resolution, Herschel will observe large complete samples of IR galaxies to redshifts of z = 2 and beyond. In combination with upcoming radio facilities such as eVLA, ASKAP, and MeerKAT, this will allow a major improvement in the study of the IR–radio correlation in the high-redshift universe.

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