THE MICROJANSKY RADIO GALAXY POPULATION

A. J. Barger, 1,2,3,4 L. L. Cowie, 4 and W.-H. Wang 4

Received 2006 April 12; accepted 2006 September 11

ABSTRACT

We use highly spectroscopically complete observations of the radio sources from the VLA 1.4 GHz survey of the Hubble Deep Field–North region to study the faint radio galaxy population and its evolution. The fraction that can be optically spectroscopically identified is fairly independent of radio flux, with about 60%–80% identified at all fluxes. We spectrally classify the sources as absorbers, star formers, Seyfert galaxies, and broad-line AGNs, and we analyze their properties by type. We supplement the spectroscopic redshifts with photometric redshifts measured from the rest-frame ultraviolet to mid-infrared spectral energy distributions. Using deep X-ray observations of the field, we do not confirm the existence of an X-ray–radio correlation for star-forming galaxies. We also do not observe any correlations between 1.4 GHz flux and R magnitude or redshift. We find that the radio powers of the host galaxies rise dramatically with increasing redshift, while the optical properties show at most small changes. Assuming that the locally determined far-infrared–radio correlation holds at high redshifts, we estimate total FIR luminosities for the radio sources. We note that the FIR luminosity estimates for any radio-loud AGNs, which we conservatively do not try to remove from the sample, will be overestimates. Considering only the radio sources with quasar-like bolometric luminosities, we find a maximum ratio of candidate highly obscured AGNs to X-ray–luminous (L_{0.5-2 keV} or L_{2-8 keV} ≥ 10^{42} ergs s^{-1}) sources of about 1.9. Finally, we use source-stacking analyses to measure the X-ray surface brightnesses of various populations. We find the contributions to the 4–8 keV light from our candidate highly obscured AGNs to be very small, and hence these sources are unable to account for the light that has been suggested may be missing at these energies.

Subject headings: cosmology: observations — galaxies: active — galaxies: distances and redshifts — galaxies: evolution — galaxies: formation

Online material: color figures

1. INTRODUCTION

In the local universe, Seyfert 2 galaxies outnumber Seyfert 1 galaxies by 4 to 1 (Maiolino & Rieke 1995), and more than half of Seyfert 2 nuclei are Compton-thick with obscuring column densities N_H > 10^{24} cm^{-2} (Maiolino et al. 1998; Risaliti et al. 1999; Guainazzi et al. 2005; Comastri 2004). In the high-redshift universe, X-ray background population synthesis models (refined after the discovery of a lower redshift distribution than expected for the hard X-ray sources; e.g., Barger et al. 2002, 2003; Szokoly et al. 2004) similarly predict a population of highly obscured active galactic nuclei (AGNs) that are missed in the deep Chandra and XMM-Newton hard X-ray surveys (e.g., Franceschini et al. 2002; Gandhi & Fabian 2003; Ueda et al. 2003; Comastri 2004; Gilli 2004; Fabian & Worsley 2004; Treister & Urry 2005; Ballantyne et al. 2006). Such theoretical predictions appear to be receiving some observational confirmation in the work of Worsley et al. (2005). Using a source-stacking analysis on the Chandra Deep Field–North (CDF-N) and Chandra Deep Field–South (CDF-S) fields, Worsley et al. (2005) found that the resolved fraction in the 6–8 keV band was only about 60%. (Worsley et al. 2004 did a similar analysis on the XMM-Newton Lockman Hole field and found a 50% resolved fraction above 8 keV.) According to these authors, the missing X-ray background (XRB) component has a spectral shape consistent with a population of highly obscured AGNs at redshifts z ~ 0.5–1.5 having obscuring column densities of N_H ~ 10^{21}–10^{24} cm^{-2}.

Of course, to derive these results, Worsley et al. (2005) had to choose which estimate of the 2–8 keV extragalactic XRB spectrum to use, and there is a great deal of uncertainty in these measurements (see Fig. 15 of Hickox & Markevitch 2006 for a summary; Worsley et al. 2005 used the XMM-Newton measurement made by De Luca & Molendi 2004, but Revnivtsev et al. 2005 found that the intensity of the XRB measured by focusing telescopes is higher than that measured by collimated experiments by about 10%–15%, possibly due to the extreme complexity of measuring effective solid angles of focusing telescopes). Indeed, Barger et al. (2002) found that the issue of whether there is a need for a substantial population of as-yet-undetected highly obscured AGNs depends critically on how the low-energy and high-energy XRB measurements tie together.

Regardless, the combination of the theoretical modeling predictions for a population of highly obscured AGNs missing from the deep X-ray surveys and the possible observational evidence for a substantial unresolved fraction of the XRB has inspired observers to try to quantify the fraction of obscured AGNs that may be being missed. Deep mid-infrared (MIR) and radio images are an obvious avenue for searching for highly obscured AGNs, since extinction in the MIR and radio is small. Various approaches using MIR or X-ray data (e.g., Alonso-Herrero et al. 2006; Polletta et al. 2006), the combination of MIR and radio data (e.g., Martínez-Sansigre et al. 2005), or the combination of MIR, radio, and X-ray data (e.g., Donley et al. 2005) have been adopted, and a candidate population of highly obscured AGNs has been identified. However, the various selection effects in these approaches...
mean that a reliable upper limit on the number of highly obscured AGNs that are undetected even in the 2–8 keV band has not yet been obtained.

In this paper we take an alternative approach to look for highly obscured AGNs at high redshifts using a pure microjansky radio survey selection. Ultradeep radio surveys are very useful for tracing the evolution of dust-obscured galaxies and AGNs. In contrast to optical surveys, which may omit dusty sources, and submillimeter surveys, which currently have low spatial resolution and are limited to small areas for any significant depth, the 1.4 GHz surveys do not suffer from extinction, provide subarcsecond positional accuracy, and cover large areas.

Although the jansky and millijansky radio source populations are dominated by powerful AGNs, at the microjansky level, the radio source population is increasingly dominated by star-forming galaxies, which produce nonthermal radio continuum at 1.4 GHz through synchrotron emission from supernova remnants. In local star-forming galaxies and radio-quiet AGNs, it is well known that the radio power is tightly correlated with the far-infrared (FIR) luminosity (e.g., Helou et al. 1985; Condon et al. 1991; Condon 1992), probably as a result of both being linearly related to the massive star formation rate. If we assume that this correlation continues to hold at high redshifts (note that there is some observational support that the correlation does extend to $z \geq 1$ from the work of Appleton et al. [2004], although the number of galaxies at the higher redshifts is relatively low), then we can use this relation to estimate the total FIR luminosity of a galaxy from its radio power alone. Indeed, even with the advent of the Spitzer Space Telescope, this is still the most robust way to estimate a galaxy’s total FIR luminosity, due to the limited MIPS sensitivities at 70 and 160 $\mu$m and the uncertainties in the conversion from 24 $\mu$m luminosity to total FIR luminosity. Although estimating total FIR luminosities from 24 $\mu$m data has been advocated (e.g., Appleton et al. 2004; Marcillac et al. 2006), the conversion depends on the assumed shape of the spectral energy distribution (SED), which is expected to change as a function of dust temperature and metallicity.

Using their Spitzer Infrared Nearby Galaxies Survey (SINGS) data, Dale et al. (2005) found a total range in rest-frame 8 $\mu$m (which corresponds to observed-frame 24 $\mu$m at $z = 2$) to total FIR luminosity ratios of more than a factor of 20. When they excluded the metal-poor dwarfs, the total range dropped to a factor of 10, which they argued should be taken as a minimum systematic uncertainty for total FIR luminosities inferred from rest-frame 8 $\mu$m fluxes alone. They cautioned that if the metal abundance of the population cannot be inferred a priori, then the uncertainties may be considerably higher. Likewise, they found that the rest-frame 24 $\mu$m to total FIR ratio spans a factor of 5 in the SINGS sample.

In addition to our assumption that the FIR-radio correlation continues to hold at high redshifts, the other possible concern with our procedure of estimating the total FIR luminosities of the radio sources using the FIR-radio correlation is the presence of radio-loud AGNs. For these sources, the radio continuum will be in excess of the level expected from star formation, and we will overestimate their total FIR luminosities. Fortunately, however, since we are only interested in obtaining upper limits on the number of highly obscured AGNs, this is not a major concern for our present analysis, and we have conservatively not made any effort to remove such sources from our sample.

Finally, we note that even in the case of the radio-quiet AGNs, we are not able to separate out the AGN contribution to the FIR luminosity from the star-forming contribution. However, since local radio-quiet AGNs are empirically observed to follow the FIR-radio correlation, we have an upper limit on the AGN FIR emission, which is sufficient for our analysis.

In this paper, we use the ultradeep 1.4 GHz observations of the the Hubble Deep Field–North (HDF-N; Richards 2000), for which we have obtained very complete spectroscopic identifications, to study the properties of the radio sample. The HDF-N has a wealth of existing multiwavelength data, including the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) Treasury Great Observatories Origins Deep Survey–North data (GOODS-N; Giavalisco et al. 2004), and the Spitzer Space Telescope Legacy GOODS-N data (PI: M. Dickinson). In addition, we have recently obtained deep wide-area J- and H-band observations using the University of Hawaii 2.2 m telescope (L. Trouille et al. 2007, in preparation), which enable us to assign robust photometric redshifts to the spectroscopically unidentified sources.

The HDF-N is also the site of the deepest X-ray image of the sky, the 2 Ms CDF-N. We use these data to examine the issue of whether there exists an X-ray–radio correlation for star-forming galaxies. In addition, we use these data to remove the X-ray–luminous ($L_{0.5–2\text{keV}} > L_{2–8\text{keV}} \geq 10^{42}$ ergs s$^{-1}$) sources from our radio-identified candidate highly obscured AGN population for tighter upper limits. Finally, we measure the X-ray surface brightnesses for our candidate highly obscured AGN population and others, which we compare with the shape and intensity of the XRB.

The structure of the paper is as follows. In § 2 we describe the radio sample and the available multiwavelength imaging and spectroscopic data. In § 3 we discuss the spectroscopic identifications of the radio sample. In § 4 we briefly describe our photometric redshift method, which uses the optical to MIR SEDs, and we show our redshift distribution for the radio sources. In § 5 we discuss the 24 $\mu$m properties of the radio sample and the difficulties with using these data to estimate FIR luminosities. In § 6 we describe our spectral classification scheme and examine the properties of the radio sample by spectral class. In § 7 we discuss the X-ray properties of the radio sample and investigate whether there is an X-ray–radio correlation for star-forming galaxies at these higher redshifts, like there is locally. In § 8 we describe the optical properties of the radio sample. In § 9 we determine the FIR luminosities of the radio sources using our redshifts and the FIR-radio correlation. We then put quantitative upper limits on the numbers of highly obscured AGNs that could have gone undetected in this deepest of hard X-ray surveys, and we discuss the implications for the history of supermassive black hole growth. In § 10 we measure the X-ray surface brightnesses of our radio-identified candidate highly obscured AGN population, as well as of other radio and X-ray populations, and we compare them with the shape and intensity of the XRB. We summarize our results in § 11.

We assume $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes are in the AB magnitude system.

2. THE DATA

2.1. Radio and X-Ray Data

Richards (2000) presented a catalog of 1.4 GHz sources detected in the Very Large Array (VLA)$^5$ map of the HDF-N, which covers a 40′′ diameter region with an effective resolution of 1.8′′. The absolute radio positions are known to 0.1′′–0.2″ rms.

$^5$ The VLA is a facility of the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Alexander et al. (2003) presented the 2 Ms X-ray image of the CDF-N, which they aligned with the Richards (2000) radio image. Near the aim point, the X-ray data reach limiting fluxes of $f_{2-8\text{keV}} \approx 1.4 \times 10^{-15}$ and $f_{0.5-2\text{keV}} \approx 1.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$. We determined the maximal radius radio circle that fits within the $\text{Chandra}$ area to be a 10$^\prime$ radius circle centered on the position R.A. = 12h36m54.29s, decl. = 62°14’16.0” (J2000.0). This also roughly matches the highest sensitivity region of the VLA observations, producing a relatively uniform radio map. Our radio sample consists of the 207 radio sources contained within this radius.

For sources within our 10$^\prime$ radius, matching X-ray counterparts from the Alexander et al. (2003) catalogs to the radio sources is not critically dependent on the choice of match radius. This can be seen from Figure 7 of Alexander et al. (2003), which shows the positional offset between the X-ray and radio sources versus off-axis angle. We chose to use a 1.5$^\prime$ search radius as a reasonable compromise between not pushing too hard on the accuracy of the data and not introducing too much random error, but only two additional sources would have been matched with a 2$^\prime$ search radius, and only three of the current sources would not have been matched with a 1$^\prime$ search radius.

Richards (2000) gave a 5 $\sigma$ completeness limit of 40 $\mu$Jy for compact sources in the central region of the map. The completeness limit is somewhat higher for extended radio sources. We independently determined the completeness of the Richards (2000) 1.4 GHz catalog by measuring the radio fluxes of a large, optically selected sample in 3$^\prime$ diameter apertures and adjusting the normalization to match the measured fluxes in the Richards (2000) catalog for the overlapping sources. Figure 1a shows that the Richards (2000) catalog is highly complete to 70 $\mu$Jy and then drops to about 50% completeness at 60 $\mu$Jy.

Biggs & Ivison (2006) have recently given a new catalog of 1.4 GHz sources using all of the $\text{A}$-array data from the VLA. This catalog is slightly more sensitive than the Richards (2000) catalog and may also be used to estimate the completeness of the Richards (2000) catalog. Within our 10$^\prime$ radius region, the new catalog contains 280 sources, of which 259 have fluxes greater than 40 $\mu$Jy, as opposed to the 207 sources in the Richards (2000) catalog. Of the 207 Richards (2000) sources, 188 have direct counterparts in the Biggs & Ivison (2006) catalog. For two other sources, the positions in the two catalogs are offset due to different centerings on the radio sources. The fluxes of the overlapping sources are in reasonable agreement. Most of the 17 Richards (2000) sources that are missing in the Biggs & Ivison (2006) catalog have optical counterparts and redshifts, so they are probably real and have just dropped below the flux limit of the Biggs & Ivison (2006) catalog. In Figure 1b we show the completeness of the Richards (2000) catalog based on the Biggs & Ivison (2006) catalog. The plot shows the ratio of the number of sources per flux bin detected in the Richards (2000) catalog to the number of sources per flux bin detected in the Biggs & Ivison (2006) catalog. Consistent with our analysis of the completeness of the Richards (2000) catalog using the optical data, this shows that the Richards (2000) sample is substantially complete above 70 $\mu$Jy but becomes progressively more incomplete at lower fluxes. In our subsequent analysis, we adopt 60 $\mu$Jy as our effective completeness limit.

2.2. Optical and Near-Infrared Data

Giavalisco et al. (2004) presented $\text{HST}$ ACS images of the HDF-N region (the GOODS-N), and Capak et al. (2004) presented ground-based deep optical imaging of a very wide-field region encompassing the GOODS-N. The ground-based data cover the whole MIPS and IRAC areas ($\approx 2.3$) in the $UBVRI'$, and $HK'$ bands. All of the images were registered to the Richards (2000) radio catalog for accurate absolute astrometry.

L. Trouille et al. (2007, in preparation) carried out deep $J$- and $H$-band imaging of the entire GOODS-N region using the Ultra-Low Background Camera (ULBCAM) on the University of Hawaii 2.2 m telescope during 2004 and 2005. ULBCAM consists of four 2k $\times$ 2k HAWAII-2RG arrays (Loose et al. 2003) with a total 16' $\times$ 16' field of view. The images were taken using a 13 point dither pattern with $\pm 30'$ and $\pm 60'$ dither steps in order to cover the chip gaps. The near-infrared (NIR) data were flattened using median sky flats from each dither pattern. The image distortion was corrected using the astrometry in the USNO-B1.0 catalog (Monet et al. 2003). The flattened, sky-subtracted, and warped images (with typical seeing 0.7$''$) were combined to form the final mosaic, which has a 20'$\times$20' area that fully covers the GOODS-N region. The final image was registered to the Richards (2000) radio catalog. The integration times at each pixel are 9 hr in $J$ and 12.5 hr in $H$, respectively, and the 5 $\sigma$ sensitivities are 0.84 and 2.06 $\mu$Jy, corresponding to 5 $\sigma$ AB magnitude limits of 24.1 and 23.1, respectively.

We measured all of the optical and NIR magnitudes at the positions of the radio sources using 3$''$ diameter apertures and...
computed them to approximate total magnitudes using an average offset for each wave band (Cowie et al. 1994).

2.3. Mid-Infrared Data

Wang et al. (2006) combined the reduced DR1 and DR2 IRAC superdeep images from the GOODS-N Spitzer Legacy Science Program first, interim, and second data release products (DR1, DR1+, DR2; Dickinson et al. 2007, in preparation), weighted by exposure time, to form 3.6, 4.5, 5.8, and 8.0 μm images that fully cover the GOODS-N area. We measured the source fluxes at the radio positions using fixed 4.8 (3.6 and 4.5 μm) and 6.0 (5.8 and 8.0 μm) diameter apertures. These apertures are approximately three times the ~1.77 (3.6 μm) to ~2" (8.0 μm) FWHM of the point-spread function (PSF) and are a good compromise between the PSF size and the source separation. We applied aperture corrections from the IRAC in-flight PSFs (2004 January), which are consistent with the ones published in the IRAC Data Handbook, to the measured fluxes. The corrected IRAC fluxes should be reasonably close to the total fluxes of the sources, because the majority of the sources are pointlike compared to the ~2" IRAC PSF. The primary errors in the photometry are caused by the high density of sources, especially at 3.6 and 4.5 μm. In these two bands, the typical distance between sources is comparable to the PSF, and the maps are confusion-limited. Consequently, both the background estimate and the aperture photometry are highly subject to blending with nearby sources.

Also, following Wang et al. (2006), we directly used the DR1+ MIPS 24 μm source list and version 0.36 MIPS 24 μm map provided by the Spitzer Legacy Program. This source catalog is flux-limited at 80 μJy and is a subset of a more extensive catalog (R. R. Chary et al. 2006, in preparation). With the 0.065 deg² area coverage, the catalog contains 1199 24 μm sources and is highly complete at 80 μJy. The source positions are based on sources detected in the deep IRAC images, and the fluxes are derived using PSF fitting. A ~0.38 offset in declination was applied to the source positions to match the radio-frame astrometry (Richards 2000). We cross-identified the MIPS sources with the radio sources by searching a 1.5" radius region around the radio positions.

2.4. Spectroscopic Data

Cowie et al. (2004b) and Wirth et al. (2004) report the results of an extensive spectroscopic survey of galaxies in the ACS GOODS-N region. We supplemented these data with spectral observations made with the Deep Extragalactic Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the Keck II 10 m telescope subsequent to the publication of these papers and with targeted observations of radio and X-ray sources (Barger et al. 2002, 2003, 2005; Cowie et al. 2004a) made with either DEIMOS or the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck I telescope. We also use redshifts obtained by Chapman et al. (2004, 2005) and Swinbank et al. (2004), adopting the Swinbank et al. (2004) NIR redshifts over the Chapman et al. (2004, 2005) optical redshifts, where available, because redshift measurements are generally more reliable when they are made from emission-line features. Where there are redshifts from both sources, the redshifts are within <0.008 of each other.

3. Radio Sample Identifications

Cross-identification of the radio sources with their counterparts is nontrivial. Some radio sources have complex structures, and it is only by inspection of overlays of the radio contours on optical through MIR images that the likely counterparts can be identified. In other cases, the counterparts are extremely red, only emerging in the NIR or MIR bands. (Reassuringly, these red cores inevitably agree with the radio positions.) The most extreme of these sources can only be identified in the Spitzer IRAC bands, which do not cover the entire radio field.

There are also cases where previous spectroscopic identifications (found through a search of the literature via the NASA/IPAC Extragalactic Database, NED) appear to be of neighboring, usually much bluer galaxies, rather than of the genuine counterparts. It is possible that some of these identifications may, in fact, be correct if the bluer structures are parts of a more extended galaxy centered on the red core. However, it is very hard to make a convincing argument that this is indeed the case, rather than, for example, that the blue source is a background galaxy lensed by the foreground red source.

Here we try to take a conservative approach to the identifications. We first determined which sources have unambiguous counterparts. These include all of the sources which have either a 5 σ ground-based z' - or H-band counterpart or an IRAC 5.4 μm counterpart lying within 1" of the radio position. This immediately identifies 195 of the sources in the sample. The dispersion of these sources around the radio positions is 0.3".

![Fig. 2.—Mosaic of the birolal source and the 11 remaining sources in our radio sample without obvious counterparts. The sources are shown in the order of Table 1, starting from the bottom-left corner and moving to the right, then looping back to the beginning of the next row and again moving to the right. The individual images are 12.5° on a side. There are three colors in the images: blue is set to be the z' image, green is set to be the J image, and red is set to be the average of 1 + z', all from the ACS GOODS-N data. The contours show the positions of the radio light. [See the electronic edition of the Journal for a color version of this figure.]]
TABLE 1

| BILOBAL SOURCE AND 11 SOURCES WITHOUT OBVIOUS COUNTERPARTS |
|-----------------------------------------------------------|
| R.A. (J2000.0) | Decl. | Radio Flux (µJy) | Redshift |
|----------------|-------|-----------------|----------|
| 12 37 25.73... | 62 11 28.50 | 5960* | 1.641b |
| 12 37 02.29... | 62 23 31.50 | 78.7 | 0.642c |
| 12 35 40.39... | 62 16 25.80 | 60.1 | ... |
| 12 35 41.00... | 62 28 20.80 | 89.0 | ... |
| 12 35 57.71... | 62 08 08.41 | 68.6 | ... |
| 12 36 08.24... | 62 15 53.00 | 59.3* | ... |
| 12 36 24.28... | 62 10 17.00 | 54.2* | ... |
| 12 36 43.88... | 62 05 59.20 | 62.5 | ... |
| 12 36 46.70... | 62 12 26.49 | 72.0 | ... |
| 12 36 51.72... | 62 05 02.49 | 57.6* | ... |
| 12 36 54.70... | 62 10 39.60 | 48.2 | ... |
| 12 37 23.05... | 62 05 39.59 | 78.5* | ... |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

We then overlaid the radio contours of the remaining 12 sources on the optical images of the field (Fig. 2). One source, with a flux of 5.96 mJy, is clearly bilobal and centered on a small red galaxy. We take this red galaxy to be the counterpart to the radio source. The remaining 11 sources have no obvious identifications, although three lie near bright galaxies (one of these could be an off-axis source; see below), and a fourth may be associated with a pair of interacting galaxies at z = 0.642. Nearly all of these are faint sources (40–80 µJy), and some may be false. (Note that Richards 2000 found a −9σ source within the HDF-N radio image, and since the probability of finding such a source in the image is much less than 1%, he concluded that the noise properties of the image are not entirely Gaussian.) However, four of the remaining 11 sources have fluxes above 70 µJy, and four (including only one of the sources with a flux above 70 µJy) are in the deeper Biggs & Ivison (2006) catalog (see Table 1). These may be real sources without counterparts from the optical to the MIR. For example, they could be very obscured or perhaps high-redshift galaxies.

We summarize the radio and optical coordinates of the bilobal source and the radio coordinates of the 11 sources without obvious counterparts in Table 1. Only one of these sources has an X-ray or 24 µm detection. This source, which has both, lies in the outer regions of a bright z = 0.459 galaxy and may be either an off-axis source in that galaxy or a faint background source that is hidden by the foreground galaxy and hence cannot be identified.

Next, we determined which of the radio sources with unambiguous optical counterparts had spectroscopic redshifts. We omitted redshifts for 12 sources with identifications in the literature (from NED), where inspection of the images suggested that the identifications may not be directly associated with the radio sources. As we have noted above, some of these identifications may be correct, but it appears safer to rely on the photometric redshifts for these sources. We summarize the omitted literature redshifts in Table 2, and we show the radio contours overlaid on the optical images for these sources in Figure 3.

Our final compilation contains 143 spectroscopic redshifts, of which 101 are already in the literature, and 42 are new to this work. In our subsequent analysis, we distinguish the 12 redshifts that we use from Chapman et al. (2004, 2005) and Swinbank et al. (2004) from our other redshifts, referring to them as the CS sources. In Figure 4 we show the fraction of radio sources that are spectroscopically identified. We see that the identified fraction is fairly independent of radio flux, with about 60%–80% of the sources identified at all fluxes.

In Figure 5 we show the R magnitude distribution for all of the sources in our radio sample (open area). We denote the spectroscopic sample with light shading and the CS sources with dark shading. Beyond R = 24, it becomes more difficult to spectroscopically identify the radio sources, while at brighter magnitudes, essentially all of the sources can be identified.

4. PHOTOMETRIC REDSHIFTS

Wang et al. (2006), using the method of Pérez-González et al. (2005), built “training-set” SEDs from 1200 galaxies in the MIPS GOODS-N sample with known redshifts and spectral types. They built seven templates, ranging from an elliptical galaxy spectrum to a blue star-forming galaxy spectrum, over the frequency range from 6 × 10^{13} to 4 × 10^{15} Hz. They then made least-squares fits of their individual source SEDs to these templates to determine the photometric redshifts and spectral types for the galaxies in their samples. They found that the method worked extremely well over a wide range of redshifts and only failed for a small number of sources. Their use of the deep J- and H-band magnitudes and the Spitzer data, in addition to the optical data, substantially improved the high-redshift end of the photometric redshift determinations.
To derive photometric redshifts for our radio sources, we similarly constructed SEDs using the optical data, the Spitzer IRAC 3.6, 4.5, 5.8, and 8.0 μm data, the Spitzer MIPS 24 μm data, and the ULBCAM NIR J- and H-band data. We then made least-squares fits to the Wang et al. (2006) templates to determine the photometric redshifts and spectral types for the galaxies in our radio sample that were detected in at least five bands. This gives us an additional 47 redshifts. Thus, in total, only 17 of our radio sources (including the 11 without any obvious counterparts) have neither a spectroscopic nor a photometric redshift. We show a comparison of the photometrically identified sources (open area) with the spectroscopically identified sources (light shaded area) in Figure 6. The CS sources are denoted by dark shading.

To derive photometric redshifts for our radio sources, we similarly constructed SEDs using the optical data, the Spitzer IRAC 3.6, 4.5, 5.8, and 8.0 μm data, the Spitzer MIPS 24 μm data, and the ULBCAM NIR J- and H-band data. We then made least-squares fits to the Wang et al. (2006) templates to determine the photometric redshifts and spectral types for the galaxies in our radio sample that were detected in at least five bands. This gives us an additional 47 redshifts. Thus, in total, only 17 of our radio sources (including the 11 without any obvious counterparts) have neither a spectroscopic nor a photometric redshift. We show a comparison of the photometrically identified sources (open area) with the spectroscopically identified sources (light shaded area) in Figure 6. The CS sources are denoted by dark shading. The gap in the spectroscopic redshift distribution between \( z \approx 1.4 \) and \( z \approx 1.9 \), known as the "redshift desert," reflects the difficulty of identifying galaxies with redshifts in this range, where \([\text{O} \, \text{ii}]\) 3727 Å has moved out of the optical window and Ly\( \alpha \) 1216 Å has not yet entered in.

5. 24 μm PROPERTIES OF THE RADIO SAMPLE

Studies based on the Infrared Space Observatory (ISO) 15 μm data found a loose correlation between the MIR emission and
the radio continuum (Cohen et al. 2000; Elbaz et al. 2002; Garrett 2002; Gruppioni et al. 2003). Appleton et al. (2004) confirmed the existence of this correlation with Spitzer data, and Marcillac et al. (2006) proposed using it to derive FIR luminosities. However, while obtaining the FIR luminosity from a radio measurement only depends on the FIR-radio correlation and the radio spectral index (and the assumption that the source is not a radio-loud AGN), obtaining the FIR luminosity from a MIR measurement strongly depends on the library of template SEDs that is used to K-correct the data.

We illustrate the difficulty with using MIR data to estimate FIR luminosities in Figure 7 (similar to Fig. 1 of Donley et al. 2005), where we show the observed 24 μm to 1.4 GHz flux ratio versus redshift. Filled (open) symbols denote sources with (without) 24 μm detections, and large open squares denote sources with soft or hard X-ray luminosities in excess of 10^{42} ergs s^{-1}. For the sources without 24 μm detections, we have adopted the 80 μJy flux limit of the 24 μm source catalog (see § 2.3). We have overplotted 24 μm to 1.4 GHz flux ratios versus redshift for redshifted template SEDs (Silva et al. 1998). It is clear that there is substantial spread in the ratio, with the 24 μm measurements being very sensitive both to redshift and to galaxy type. For the most part, the data points have values that are within the range expected from the redshifted template SEDs; however, there are also a number of sources not detected at 24 μm, including many of the absorbers (large open diamonds; see § 6). The absorbers are most likely radio-loud AGNs, which would not be expected to have SEDs like those shown.

We note that Donley et al. (2005), in their search for highly obscured AGNs, defined a selection threshold of q = log (S_{24 μm}/S_{1.4 GHz}) < 0 to classify a galaxy as probably having an AGN. Based on the SEDs used in our Figure 7, this criterion might result in some contamination by ultraluminous infrared galaxies, and, to a lesser extent, by spirals, as both of those SEDs dip below q = 0. We do see sources below this value that do not have X-ray luminosities typical of an AGN and are not spectroscopically classified as absorbers, and some of these sources may be highly obscured AGNs, but clearly we cannot rely on the 24 μm data to determine their FIR luminosities.

6. PROPERTIES OF THE RADIO SAMPLE
BY SPECTRAL CLASS

For our spectroscopically identified sources, we classified the optical spectra into four spectral classes, roughly following the procedure used by Sadler et al. (2002) to analyze low-redshift 1.4 GHz samples. We classified sources without any strong emission lines [EW(O ii) < 3 A or EW(Hα + N ii) < 10 A] as "absorbers," sources with strong Balmer lines and no broad or high-ionization lines as "star formers," sources with [Ne v] or C iv lines or strong [O iii] [EW(O iii) 5007 A] > 3EW(H/β)] as "Seyfert galaxies," and, finally, sources with optical lines having FWHM line widths >2000 km s^{-1} as "broad-line AGNs." We have not classified one high-redshift source at z = 2.2032. This source must be a strong star former because it has UV absorption lines; however, its [O iii] emission is redshifted into the NIR and hence cannot be measured with our spectra. We have also not attempted to spectroscopically classify the CS sources, which are generally of this type.

6.1. Radio-to-Optical Ratios by Spectral Class

Some radio quasar studies have found bimodal distributions of rest-frame radio-to-optical ratios (e.g., Kellermann et al. 1989; Stocke et al. 1992; Ivezic et al. 2002; however, see White et al. 2000; Cirasuolo et al. 2003). These have been interpreted as evidence that quasars come in two distinct populations, "radio-loud" and "radio-quiet." The boundary value between radio-loud and radio-quiet has been inferred to be f_{GHz}/f_{2500} Å = 10 (Stocke et al. 1992).
For our study, we define a rest-frame radio-to-optical ratio of 
\[ R = \frac{f_{1.4\text{GHz}}}{f_{6500\text{\AA}}} \]
This is an approximately equivalent ratio, since the K-correction to go from 5 to 1.4 GHz is very similar to the K-correction to go from 2500 to 6500 \( \text{\AA} \), assuming spectral indices of \( \alpha = 0.8 \) for \( f_r \propto \nu^{-\alpha} \) in both cases (Yun et al. 2001; Zheng et al. 1997).

In Figure 8 we show a histogram of logarithmic \( R \) for our \( z < 1.6 \) spectroscopically classified radio sample. We have such uniform and complete wavelength coverage for all of the radio sources that we have just interpolated between our measurements to obtain rest-frame AB 6500 \( \text{\AA} \) magnitudes. We have restricted the plot to sources with \( z < 1.6 \) so that our interpolation remains valid. We have also K-corrected the radio measurements to rest-frame 1.4 GHz. The star formers clearly dominate the microjansky sample, as was inferred from previous work (e.g., Windhorst et al. 1995; Richards et al. 1998; Richards 2000; Roche et al. 2002).

Unfortunately, we do not have a large enough sample of Seyfert galaxies plus broad-line AGNs to investigate whether there is bimodality in the rest-frame radio-to-optical ratios. However, we can see that all of the spectral classes show a wide range in radio-to-optical ratios. Thus, in contrast to the conclusions of Machalski & Condon (1999) from their study of millijansky radio sources in the Las Campanas Redshift Survey, we do not find this ratio to be a useful discriminator between star-forming galaxies and AGNs. Afonso et al. (2005) came to a similar conclusion using the Phoenix Deep Survey, which reaches into the sub-100 \( \mu \text{Jy} \) regime. They argued that the radio morphology and polarimetry used by Machalski & Condon (1999) to identify AGNs results in the misclassification of many low-power AGNs, and these sources would blur the distinction if properly classified as AGNs. Since the radio-to-optical ratio does not appear to have much diagnostic power for our sample, we do not use it subsequently.

6.2. Radio Power and Redshifts by Spectral Class

In Figure 9 we show histograms of the (a) logarithmic radio powers and (b) redshifts for the spectroscopically classified radio sample (shaded area). We calculate the rest-frame radio powers from the equation

\[ P_{1.4\text{GHz}} = 4\pi d_L^2 S_{1.4\text{GHz}}10^{-28}(1+z)^{-\alpha} \text{ergs s}^{-1} \text{Hz}^{-1}. \] (1)

Here \( d_L \) is the luminosity distance (cm), \( S_{1.4\text{GHz}} \) is the 1.4 GHz flux density (\( \mu \text{Jy} \)), and \( \alpha \) is the radio spectral index, which we take to be 0.8 (Yun et al. 2001).

The bulk of the star formers tend to lie at the lower radio powers. The redshift distribution for the Seyfert galaxies plus broad-line AGNs stretches to higher redshifts than the star formers and the absorbers, although the absorbers in particular become more difficult to identify spectroscopically at \( z > 1 \). We show that this is a selection effect by including on Figure 9b the redshift distribution for the photometrically identified absorbers classified using their SEDs (see § 5.4) (open area).

7. X-RAY PROPERTIES OF THE RADIO SAMPLE

An X-ray–radio correlation for star-forming galaxies has been determined locally by a number of authors (e.g., Bauer et al. 2002; Ranalli et al. 2003; Grimm et al. 2003; Gilfanov et al. 2004), suggesting that the X-ray emission in star-forming galaxies can be used as an indicator of the star formation rate. These same authors, using a small sample of sources in the CDF-N (at the time, only the 1 Ms Chandra data were available; Brandt et al. 2002).
et al. 2001), also claim that the linear relation extends to higher redshifts \((z < 1.3)\). With our highly spectroscopically complete, clearly selected sample from just one flux band (1.4 GHz), we are in an excellent position to test whether the local X-ray–radio correlation does indeed continue to hold to higher redshifts.

In Figure 10a (10b), using different symbols for the different spectral classes, we plot 2–8 keV (0.5–2 keV) luminosity over 1.4 GHz power (we use the ratio to remove the redshift effect and improve the dynamic range) versus 1.4 GHz power for the spectroscopically identified galaxies in our radio sample that were significantly detected by Alexander et al. (2003) in the 2–8 keV (0.5–2 keV) band. We calculated the rest-frame 1.4 GHz powers using equation (1), and we calculated the rest-frame hard (soft) X-ray luminosities from

\[
L_X = 4\pi d_L^2 f_X (1 + z)^{\Gamma - 2} \text{ ergs s}^{-1}.
\]

Here \(d_L\) is the luminosity distance (cm), \(f_X\) is the observed-frame hard (soft) X-ray flux (ergs cm\(^{-2}\) s\(^{-1}\)), and \(\Gamma\) is the photon index, which we take to be 1.8 for all of the sources. Note that using the individual photon indices (rather than the universal power-law index of \(\Gamma = 1.8\)) to calculate the \(K\)-corrections would result in only a small difference in the rest-frame luminosities (Barger et al. 2002).
We assume that any source more X-ray luminous than $10^{42}$ erg s$^{-1}$ is very likely to be an AGN on energetic grounds (Zezas et al. 1998; Moran et al. 1999), so we illustrate the ratio of this fixed hard (soft) X-ray luminosity to the 1.4 GHz power versus the 1.4 GHz power with a diagonal line in the figures. We note that since none of the star-forming galaxies (filled diamonds) show any obvious AGN signatures in their optical spectra, those with $L_X \geq 10^{42}$ erg s$^{-1}$ are most likely to be obscured AGNs.

With a dashed horizontal line, we show the local hard (soft) X-ray–radio relation found by Ranalli et al. (2003; their eqs. [13] and [9], respectively). We have converted their 2–10 keV relation to 2–8 keV, assuming a photon index of $\Gamma = 1.8$. Although in Figure 10a we have too few significantly hard X-ray–detected, star-forming galaxies with $L_{2–8\text{keV}} < 10^{42}$ ergs s$^{-1}$ (large open diamonds) to identify any kind of correlation, in Figure 10b we can see the correlation that previous authors had identified. However, several radio-powerful star formers significantly detected in soft X-rays lie well below the apparent correlation and may be the luminous edge of the X-ray undetected population. In fact, it is important to stress that the above figures only include X-ray–detected sources, not upper limits. Including the upper limits would be the true test of whether a correlation actually exists or whether one is just observing the upper end of the distribution and hence being fooled into thinking that there is a correlation when, in actuality, it is merely a selection effect.

Unfortunately, from Figures 10c and 10d we can see that the apparent correlation is indeed merely a selection effect. Here we plot only the spectroscopically identified star formers that are not significantly detected in the 2–8 and 0.5–2 keV bands, respectively (downward-pointing arrows). We calculated the upper limits by determining the off-axis position for each source on the X-ray image and then assigning an upper bound to the X-ray flux using a radially symmetric formula based on the detection thresholds in Alexander et al. (2003). We checked the X-ray exposure map to make sure that none of the radio sources lie in anomalous regions, such as chip gaps. The diagonal and horizontal lines are as before. The first thing to note is that even with the 2 Ms exposure, we do not have the sensitivity to measure the bulk of the star-forming galaxy population in X-rays. The second thing to note is that—again seen most clearly in the soft X-ray figure—the upper limits are not consistent with the Ranalli et al. (2003) relation.

We note that some of the sources in Figure 10 may be radio-loud AGNs, but anyone using the supposed correlation with their X-ray data is going to be faced with that uncertainty. Thus, the fact that we do not confirm the existence of an X-ray–radio correlation at these redshifts, even with our knowledge of the optical spectra of the sources, is a major concern for those who want to infer star formation rates for their galaxies. Although there are attractions to measuring a star formation history based on X-ray surveys because it avoids problems of obscuration (e.g., Norman et al. 2004), we are forced to conclude that it is not easy to do so.

8. OPTICAL PROPERTIES OF THE RADIO SAMPLE

In Figure 11a we plot 1.4 GHz flux versus $R$ magnitude for the radio sample. Interestingly, there is no observed correlation between 1.4 GHz flux and $R$ magnitude, which helps to explain the uniformity of the spectroscopically identified fraction with radio flux (see Fig. 4). We illustrate this in histogram form in Figure 11b, where we plot number versus $R$ magnitude for all of the radio sources in our sample, divided into five radio flux bins. The $R$ magnitude distribution is consistent with being drawn from an invariant population. This result differs from that of Georgakakis et al. (1999) and Afonso et al. (2005), who found fainter median $R$ magnitudes with decreasing radio flux density. The most likely reason for the discrepancy is that the optical observations used by those authors were much shallower, probing only to $R = 22.5$.

In Figure 12a we show radio flux versus redshift for the spectroscopically (filled symbols) and photometrically (open squares) identified sources in the radio sample. We plot the unidentified sources at $z < 0$. Again we see no correlation between the two variables. In Figure 12b we show this in histogram form, plotting number versus redshift for all of the radio sources with either spectroscopic or photometric redshifts, divided into five radio flux bins. The redshift distribution is consistent with being invariant with radio flux, although the selection of optically bright sources through the spectroscopic identification process may mean that we are missing the higher redshift tail of the redshift distribution function. Thus, probing to fainter radio fluxes does not sample to higher redshifts (Condon 1989).
This invariance in both the optical apparent magnitudes and the redshifts of the host galaxies is a striking result. In Figure 13 we plot rest-frame AB 4500–8500 Å color versus (a) redshift and (b) 1.4 GHz flux for the spectroscopically (filled symbols) and photometrically (open squares) identified radio sources. Again, our uniform and complete wavelength coverage for all of the radio sources means that we can just interpolate between our measurements to obtain the rest-frame colors. We only use redshifts up to \( z = 1.2 \) so that our interpolation remains valid. The solid and dotted lines show the rest-frame AB 4500–8500 Å color of an elliptical and irregular galaxy, respectively, using Coleman et al. (1980). In both plots, there is very little color variation with redshift. The radio sources are clearly drawn from the same host galaxy population, and the host galaxy properties are not evolving much with redshift.

In Figure 14a we plot the absolute rest-frame \( R \) magnitude, \( M_R \), versus redshift for the spectroscopically (filled symbols) and photometrically (open squares) identified radio sources, interpolating between our measurements to obtain rest-frame AB 6500 Å, and restricting to \( z < 1.6 \) so that our interpolation remains valid. The approximate effect of our \( R \sim 24 \) spectroscopic selection limit on \( M_R \) is shown by the dotted curve. The median absolute magnitude at \( z < 0.4 \) is \( M_R = -21.4 \), while that between \( z = 0.4 \) and \( z = 0.8 \) is \( M_R = -21.5 \), so there may be a weak evolution to brighter magnitudes at higher redshift. However, this evolution is small, particularly when passive evolution of the galaxies is taken into account. At no redshift do the host galaxies become much brighter than \( M_R = -23 \). Thus, we see a narrow range in \( M_R \) with redshift (dashed lines), which suggests that the radio sources are chosen from approximately \( L^+ \) optical galaxies at all redshifts. At a very crude level, the radio hosts are standard candles in their optical properties.

In Figure 14b we plot \( M_R \) versus 1.4 GHz power. Even though the galaxy hosts have similar optical luminosities at all redshifts, we can see from the figure that they have a wide range of radio powers (see also Cirasuolo et al. 2003). Thus, the radio powers of the host galaxies must be rising dramatically with increasing redshift, while the optical properties of the host galaxies are not changing. We can see this dramatic evolution in Figure 15, which shows the spectroscopically (filled symbols) or photometrically (open symbols) identified radio sample.
squares) identified radio sample in a redshift versus 1.4 GHz power plot. The vertical dashed and solid lines show the radio powers (see § 9 for how we determined these) corresponding to a luminous infrared galaxy (LIRG; $10^{11} L_{\odot} \leq L_{\text{FIR}} < 10^{12} L_{\odot}$) and an ultraluminous infrared galaxy (ULIRG; $L_{\text{FIR}} \geq 10^{12} L_{\odot}$), respectively. All of the ULIRGs in the 1.4 GHz sample to a completeness limit of $60\mu Jy$ should be detected to $z \approx 1.3$.

Interestingly, we see from Figure 15 that only a narrow range of luminosities is observed at each redshift and that very high-luminosity sources are primarily found at high redshifts ($z \approx 1$). We therefore conclude that similar optical galaxies (see Fig. 14a) are hosting more powerful radio galaxies at higher redshifts. (See Cowie et al. 2004a for a quantitative description of the evolution of the 1.4 GHz luminosity function.)

We expand on this result in Figure 16, where we show 1.4 GHz flux versus 1.4 GHz power. Here we denote the different redshift intervals by different symbols ($z < 0.5$, filled squares; $0.5 \leq z < 1$, filled triangles; $1 \leq z < 2$, open squares; $z \geq 2$, open circles). We see a series of increasing luminosity slices with increasing redshift. The reason for this effect was first suggested by Condon (1989) based on the radio source counts. At low redshifts ($z \leq 1$), the radio surveys are dominated by the most luminous sources in each redshift shell because the radio population is experiencing such a dramatic luminosity evolution. This is unlike any other wavelength survey, where sources are generally picked up throughout the whole volume distribution. However, at higher redshifts, the evolution slows, and a wider range of luminosities is observed.
Figure 16 contradicts the suggestion by Ciliegi et al. (2005) that most of the faintest radio sources may be associated with relatively low radio luminosity sources at relatively modest redshifts rather than with high radio luminosity AGNs at high redshifts. In fact, the faintest radio sources have a wide range of radio powers and redshifts, with the higher radio powers corresponding to the higher redshifts.

9. UPPER LIMITS ON HIGHLY OBSCURED AGNs

An important goal of the present work is to determine an upper limit on the number of AGNs with quasar-like bolometric luminosities (~4 × 10^{45} ergs s^{-1}; see below) that could be highly obscured—such that the light emerges in the FIR—and hence not be detected in current deep X-ray surveys. This determination will be an upper limit, since for any of the radio sources, it is likely that much of the FIR light will be due to star formation rather than to AGN activity. Moreover, such a determination will contain radio-loud sources, where the FIR-radio correlation substantially overestimates the FIR.

We calculate total FIR luminosities for the radio sources, assuming that the FIR-radio correlation for star formers and radio-quiet AGNs holds at high redshifts, and assuming that the sources are well described by this correlation. Following Barger et al. (2001), we use the FIR-radio correlation given in Sanders & Mirabel (1996) with q = 2.35 that they find holds for sources covering several orders of magnitude in FIR luminosity. Then \( f_{\text{FIR}} = 8.4 \times 10^{14} f_{1.4}^{0.3} \), where \( f_{1.4}^{0.3} \) is the rest-frame flux at 1.4 GHz.

Assuming a synchrotron spectrum with a spectral index of 0.8 (Yun et al. 2001), we can calculate the total FIR luminosity from the observed 1.4 GHz flux using

\[
L_{\text{FIR}} = 4\pi d_L^2 (8.4 \times 10^{14} f_{1.4}(1 + z)^{-0.2},
\]

where \( d_L \) is the luminosity distance in cm and \( f_{1.4} \) has units of ergs cm^{-2} s^{-1} Hz^{-1}.

Of particular interest for our analysis are the sources that do not also have high (~10^{46} ergs s^{-1}) X-ray luminosities. Quasars are typically defined as having 2–8 keV X-ray luminosities ~10^{46} ergs s^{-1}, which, with a factor of 35 bolometric correction (e.g., Elvis et al. 1994; Kuratskiewicz et al. 2003), would roughly correspond to ULIRG luminosities. Thus, we consider any ULIRGs that do not have high X-ray luminosities to be our primary candidates to contain highly obscured AGNs.

In Figure 17 we plot redshift versus total FIR luminosity for the sources with ULIRG (vertical line) luminosities \( L_{\text{FIR}} \geq 4 \times 10^{45} \) ergs s^{-1}. We denote sources with spectroscopic redshifts by filled symbols and sources with photometric redshifts by open squares. We circle the sources that have either hard (2–8 keV) or soft (0.5–2 keV) X-ray luminosities ~10^{46} ergs s^{-1}. The dotted curve shows the 60 \( \mu \)Jy completeness limit for the radio sample. The dashed horizontal line shows an adopted upper redshift cutoff of \( z = 2 \), which is a compromise to keep our...
ULIRG selection as uniform as possible (since the radio completeness limit begins to cut out the lower luminosity ULIRGs at $z \geq 1.3$), while still retaining a statistically significant sample of sources.

In Figure 18a we show histograms of the logarithmic total FIR luminosities of the $z \leq 2$ radio sources with either spectroscopic or photometric redshifts and ULIRG luminosities divided into two categories: high X-ray luminosity sources (either $L_{0.5-2 keV} \geq 10^{42} \text{ ergs s}^{-1}$ and low X-ray luminosity sources (both $L_{0.5-2 keV}$ and $L_{2-8 keV} < 10^{42} \text{ ergs s}^{-1}$). There are 38 sources in the low X-ray luminosity histogram and 20 sources in the high X-ray luminosity histogram. Excluding the bilobal source (the source with the highest FIR luminosity estimate in Fig. 18, which is likely a substantial overestimate for this radio-loud AGN) from being considered a candidate to contain a highly obscured AGN, we find a maximum ratio of highly obscured AGN candidates to high-luminosity X-ray sources of 1.9 for radio sources in the quasar class. We stress again that this is an upper limit, since it includes star-forming ULIRGs as well as radio-loud AGNs, where the FIR-radio correlation is overestimating the FIR luminosity. Even if all 17 sources without photometric redshifts (11 of which do not have any obvious counterparts) were assumed to have ULIRG luminosities, to lie at $z \leq 2$, and not to be X-ray luminous, the ratio would only increase to 2.7.

To show the classes of sources that are comprising the low X-ray luminosity population, in Figure 18b we divide the population into absorbers, star formers, and “other.” The latter category includes spectroscopically unclassified sources and sources with only photometric redshifts. In principle, we should be able to exclude the absorbers, which are presumably radio-loud AGNs in the centers of elliptical galaxies, from being considered candidates to contain highly obscured AGNs. However, in practice, apart from the bilobal source, we leave the absorbers in because of the difficulties in distinguishing between radio-loud and radio-quiet AGNs, as discussed in § 6.1.

In Figure 19 we show in two redshift bins the number densities of radio sources with either spectroscopic or photometric redshifts and $L_{FIR} \geq 4 \times 10^{45} \text{ ergs s}^{-1}$, divided according to X-ray luminosity: diamonds denote sources with either $L_{0.5-2 keV}$ or $L_{2-8 keV} \geq 10^{42} \text{ ergs s}^{-1}$, and squares denote sources with both soft and hard X-ray luminosities $< 10^{42} \text{ ergs s}^{-1}$. Squares are slightly offset for clarity. Poissonian 1 $\sigma$ uncertainties are based on the number of sources in each redshift interval.

In Figure 20 we again plot redshift versus total FIR luminosity for the radio sample with LIRG luminosities. Filled squares and filled circles (the latter are CS sources) denote spectroscopic redshifts, and open squares denote photometric redshifts. Large, open circles denote sources that have either $L_{0.5-2 keV}$ or $L_{2-8 keV} \geq 10^{42} \text{ ergs s}^{-1}$. The dotted curve shows the 60 $\mu m$ completeness limit of the radio sample. The two solid vertical lines show the minimum luminosities of a LIRG and a ULIRG. The dashed horizontal line shows an upper redshift cutoff of $z = 0.7$ to provide an upper limit for the radio-loud AGN across a range of redshifts. The ratio continues to stay about the same at lower FIR luminosities, with values of 2 and 1.8 for the lower and higher redshift bins.

We can get a rough check on whether the upper bound on the ratio of the difficulties in distinguishing between radio-loud and radio-quiet AGNs, as discussed in § 6.1.

In Figure 20 we again plot redshift versus total FIR luminosity, for the radio sources with LIRG luminosities (4 $\times$ 10$^{44} \leq L_{FIR} < 4 \times 10^{45} \text{ ergs s}^{-1}$, vertical lines). The dashed horizontal line shows an adopted upper redshift cutoff of $z = 0.7$. The ratio of highly obscured AGN candidates to high X-ray luminosity sources does not appear to be changing much with redshift, with values of 2 and 1.8 for the lower and higher redshift bins.

Models of the XRB generally require a population of near-Compton-thick sources ($N_{HI} \sim 10^{25} - 10^{24} \text{ cm}^{-2}$). Typical estimates are, on average, for 2–3 times as many such sources as X-ray–detected sources (e.g., Fabian & Worsley 2004; Treister & Urry 2005). However, such obscured sources may preferentially lie at luminosities lower than quasar luminosities (e.g., Ballantyne et al. 2006). Thus, our upper limit of 1.9 for the ratio of quasar-luminosity but not X-ray–luminous sources to quasar-luminosity, X-ray–luminous sources may be consistent with these results.
If we assume that a roughly factor of 2 ratio of highly obscured AGN candidates to high X-ray luminosity sources applies to the quasar luminosity population and shows no redshift effect, then we estimate that the accreted supermassive black hole mass density determined by Barger et al. (2005) for broad-line AGNs (their eq. [9]) will increase to $3.6 \times 10^5 \ M_\odot \ Mpc^{-3}$. Although this is still within $2 \sigma$ of the local supermassive black hole mass density found by Yu & Tremaine (2002) of $(2.9 \pm 0.5) \times 10^5 \ M_\odot \ Mpc^{-3}$ for $h = 0.7$, it does not leave much room for the obscured accretion from the optically narrow AGNs. Applying the same factor of 2 corrections to equations (6) and (7) from Barger et al. (2005), which give the accreted supermassive black hole mass density for all spectral types assuming bolometric corrections, respectively, of 85 and 35 for the optically narrow AGNs, would increase these numbers to $12 \times 10^5$ and $6.3 \times 10^5 \ M_\odot \ Mpc^{-3}$. This could be viewed as a consistency check that there are not that many luminous obscured AGNs.

10. CONTRIBUTIONS TO THE X-RAY LIGHT

We would now like to understand what fraction of the X-ray light is coming from the different X-ray and radio populations, especially from the radio-identified ULIRG population. To study this, we performed source-stacking analyses on the CDF-N 2 Ms exposure, restricting to a 9.5' radius circle rather than the 10' radius circle used elsewhere in this paper, since a few of the radio sources in the 10' radius circle lie just outside the X-ray image.

For each sample, we first measured the X-ray fluxes of all of the sources in each of four passbands, 0.5–1, 1–2, 2–4, and 4–8 keV, using the images and exposure maps given in Alexander et al. (2003). For the X-ray sample, we measured the fluxes in the four passbands of all of the sources in the Alexander et al. (2003) catalog (detected in any passband) that lie in the 9.5' radius region. (Note that Worsley et al. 2005 found an increase in total resolved flux of about 2%–5% in the >2 keV bands when they applied the systematic flux correction determined by Bauer et al. (2004) to account for Eddington bias and some additional aperture/photometry effects that were not considered in Alexander et al. 2003, but we have not applied that correction here.)

To calculate the contribution to the extragalactic background light (EBL) from a given sample, we summed the fluxes in the 9.5' radius circle and divided by the corresponding area. We did not exclude any sources from the summations, even if a source were not significantly detected in a particular band or had a measured negative flux in the band. This simple averaging is not optimal, since the errors in the X-ray fluxes are smaller at smaller off-axis angles, but it avoids weighting the smaller central region more highly.

To estimate the uncertainties on our surface brightness measurements, we first generated a grid of 60,000 points in the 9.5' radius area that are separated from each other by more than 4'' (the aperture diameter used to measure the counts in the X-ray sources) and are located more than 6'' away from any known X-ray source. We next measured the fluxes in each of our four X-ray passbands at these 60,000 positions. This serves as our base file. Then, for each sample for which we want to determine the uncertainties, we randomly generate a number (which matches the number of sources in the sample) of integers between 1 and 60,000 and use the fluxes corresponding to those positions in our base file. We do this 1000 times, which gives us 1000 flux values for each of the four passbands. We then order those values from the most negative to the most positive and use the 68% confidence interval to determine our uncertainties. (Most of our uncertainties are much smaller than the data points.)

In Figure 21 we show the EBL from the X-ray sources in the Alexander et al. (2003) catalog with filled diamonds. Coincidentally, they match very well the 2–10 keV XRB measurement made by Revnivtsev et al. (2005) from a reanalysis of the HEAO1/A2 data (thick horizontal lines; the thickness denotes the uncertainty range on their measurement). Note that we converted the Revnivtsev et al. (2005) 2–10 keV measurement to 2–4, 4–8, and 8–10 keV by adopting a photon index of 1.4. We chose this determination to compare with since the A2 or Cosmic X-Ray Experiment instrument was especially designed for accurate measurements of the XRB over a very wide sky solid angle (e.g., Marshall et al. 1980; Boldt 1987; Gruber et al. 1999), and the design of its detectors allows the internal instrumental background to be separated from the XRB with almost absolute accuracy (Rothschild et al. 1979; Boldt 1987).

However, for this work, we are not interested in accurately determining the resolved fraction of the XRB. Such an analysis would require integrating the known log N–log S distribution to take into account the rare, bright sources that are not sampled in this deep pencil-beam survey, extrapolating the number counts to take into account the sources with fainter fluxes, and deciding which of the XRB measurements to compare with. Indeed, this was done by Moretti et al. (2003), and there is very good agreement between their result and the Revnivtsev et al. (2005) measurement. Rather, it is sufficient for us to measure the X-ray surface brightnesses from the known X-ray sources in the CDF-N and see that they are roughly consistent with the
uncertainties on their measurement. The thickness of the lines represents the 1.4 photon index of the XRB normalized to the highest energy bins of the 0.5–2 keV band. Indeed, the percentages are about a factor of 5 lower than those predicted for $N_\mathrm{H} \sim 10^{24} \, \text{cm}^{-2}$ sources at these energies in typical XRB synthesis models (e.g., Comastri et al. 2006).

However, the inverse statement that some of these non–X-ray–luminous or X-ray–undetected radio sources contribute highly obscured AGNs is true. We can see this by comparing the shapes of the X-ray surface brightness measurements for the various samples with the shape of the XRB. To make it easier to do the comparisons, in Figure 21 we normalize the 1.4 photon index of the XRB to the surface brightnesses in the highest energy bin for all but the X-ray sample and the X-ray sample without radio counterparts (to avoid cluttering up the figure too much). We can see that the shape of the surface brightness measurements for the radio sample is slightly softer than that of the XRB, while the shape of the surface brightness measurements for the X-ray sample without radio counterparts is slightly harder than the XRB. However, the shapes of the surface brightness measurements for the non–X-ray–luminous radio sample and the X-ray–undetected radio sample both appear much harder than that of the XRB. This result suggests that these two populations are consistent with containing highly obscured AGNs.

One might wonder how the shapes of the X-ray surface brightness measurements for the non–X-ray–luminous radio sample and for the X-ray–undetected radio sample vary with redshift. We show this in Figures 22a and 22b for the redshift intervals $z = 0–0.5$ (squares), 0.5–1.5 (diamonds), and 1.5–3 (triangles). The filled symbols in Figure 22a denote the non–X-ray–luminous radio sample, and the open symbols in Figure 22b denote the X-ray–undetected radio sample. Small offsets have been applied in the $x$-direction to the diamonds and to the triangles for clarity. The uncertainties are again the 68% confidence intervals. We normalize the highest energy bins of the $z = 0.5–1.5$ and $z = 1.5–3$ samples to the 1.4 photon index of the XRB for comparison. In both figures, we can see that the lowest redshift interval sample (squares) is quite soft due to the contributions from star-forming galaxies, while the higher redshift interval samples are hard due to the obscured nature of the sources.
Since in § 9 we focused on the $z \leq 2$ radio-identified ULIRG sample, we now repeat our source-stacking analyses using only these data. Our results are shown in Figure 23. We use filled squares to denote the X-ray surface brightnesses measured for the $z \leq 2$ ULIRG sample with X-ray–luminous ($L_{1.4\text{GHz}} \geq 10^{22} \text{ergs s}^{-1}$) counterparts in the Alexander et al. (2003) catalog (solid squares), without X-ray luminous counterparts (open triangles), and without X-ray counterparts at all (open squares). For comparison purposes, the diagonal solid lines show the 1.4 photon index of the XRB normalized to the highest energy bins of the X-ray–luminous and non–X-ray–luminous samples. The horizontal solid lines show the 2–10 keV XRB measurement of Revnivtsev et al. (2005) converted into narrower energy bands by adopting a photon index of 1.4. The thickness of the lines represents the uncertainties on their measurement.

![Figure 23](image.png)

**Figure 23.**—X-ray surface brightness vs. energy measured within a 9.5′ radius circle for the $z \leq 2$ radio-identified ULIRG sample with X-ray–luminous ($L_{1.4\text{GHz}} \geq 10^{22} \text{ergs s}^{-1}$) counterparts in the Alexander et al. (2003) catalog (solid squares), without X-ray luminous counterparts (open triangles), and without X-ray counterparts at all (open squares). For comparison purposes, the diagonal solid lines show the 1.4 photon index of the XRB normalized to the highest energy bins of the X-ray–luminous and non–X-ray–luminous samples. The horizontal solid lines show the 2–10 keV XRB measurement of Revnivtsev et al. (2005) converted into narrower energy bands by adopting a photon index of 1.4. The thickness of the lines represents the uncertainties on their measurement.

11. SUMMARY

In this paper we analyzed the nature and evolution of microjansky radio sources using a highly spectroscopically complete, deep VLA survey of the HDF-N region. We supplemented the spectroscopic identifications with photometric redshifts measured from the rest-frame ultraviolet to MIR spectral energy distributions. Our results are as follows:

1. We found that the fraction of radio sources that can be optically spectroscopically identified is fairly independent of radio flux, with about 60%–80% identified at all fluxes. We spectrally classified the galaxies into four spectral types: absorbers, star formers, Seyfert galaxies, and broad-line AGNs.

2. We did not confirm the existence of an X-ray–radio correlation for star-forming galaxies in either the hard or soft X-ray bands. Previous claims of such a correlation appear to be the result of selection effects.

3. We did not observe any correlation between 1.4 GHz flux and $R$ magnitude, which helps to explain the uniformity of the spectroscopically identified fraction with radio flux. Previous claims of the existence of such a correlation were likely due to the much shallower optical observations that were used in those studies.

4. We also did not observe any correlation between 1.4 GHz flux and redshift for the spectroscopically and photometrically identified sources. The redshift distribution is consistent with being invariant with radio flux, although we may be missing the higher redshift tail of the redshift distribution function due to optical spectroscopic bias.

5. The observed invariance in the rest-frame colors and only small amount of change in the absolute magnitudes of the host galaxies suggests that radio observations sample the same type of host galaxies at all redshifts and that the host galaxy properties are not evolving much with redshift.

6. There is dramatic evolution in the radio powers of the host galaxies with increasing redshift, and similar optical galaxies are hosting more powerful radio galaxies at higher redshifts. A quantitative description the evolution of the 1.4 GHz luminosity function can be found in Cowie et al. (2004a).

7. Assuming that the locally determined FIR-radio correlation holds at high redshifts, we estimated total FIR luminosities for the radio sources. We note that these will be overestimates in the case of radio-loud AGNs, but we conservatively did not try to remove the radio-loud AGNs from the sample, since we are only determining upper limits. For the radio sources with total FIR luminosities comparable to quasar-like bolometric luminosities, we obtained an upper limit of 1.9 for the ratio of candidate highly obscured AGNs to X-ray–luminous sources.

8. We measured the X-ray surface brightnesses for various X-ray and radio populations within a 9.5′ radius circle to determine their contributions to the X-ray light. For the known X-ray sources in the CDF-N, we found our measurements to be (coincidentally) consistent with the HEAO1/A2 XRB measurement made by Revnivtsev et al. (2005). We found that the Richards (2000) radio sample contributes half of the 4–8 keV light, which is also how much the X-ray sources without radio counterparts contribute. However, most of the light from the radio sample comes from the X-ray–luminous radio sources. The non–X-ray–luminous and X-ray–undetected subsamples contribute only 2.3% ± 0.4% and 1.2% ± 0.3%, respectively. This tells us that the current radio source population cannot account for the background light that one might think is missing at these energies. However, the shapes of the surface brightness measurements for these two subsamples both appear much harder than that of the XRB, which suggests that these two populations are consistent with containing highly obscured AGNs. For the $z \leq 2$ radio-identified ULIRG sample, we found that the X-ray–luminous subsample contributes a very substantial one-quarter of the 4–8 keV light, while the non–X-ray–luminous and X-ray–undetected
subsamples each contribute less than a percent. Again, the shapes of the latter two subsamples are considerably harder than the XRB and hence are consistent with containing highly obscured AGNs.

We thank the referee for helpful comments that improved the manuscript. We thank L. Silva for providing the template spectral energy distributions. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We gratefully acknowledge support from NSF grants AST 02-39425 (A. J. B.) and AST 04-07374 (L. L. C.), the University of Wisconsin Research Committee with funds granted by the Alfred P. Sloan Foundation, and the David and Lucile Packard Foundation (A. J. B.).

REFERENCES

Afonso, J., Georgakakis, A., Almeida, C., Hopkins, A. M., Cram, L. E., Mobasher, B., & Sullivan, M. 2005, ApJ, 624, 135
Alexander, D. M., et al. 2003, AJ, 126, 539
Alonso-Herrero, A., et al. 2006, ApJ, 640, 167
Appleton, P. N., et al. 2004, ApJS, 154, 147
Ballantyne, D. R., Everett, J. E., & Murray, N. 2006, ApJ, 639, 740
Barger, A. J., Cowie, L. L., Brandt, W. N., Capak, P., Garmire, G. P., Hornschemeier, A. E., Steffen, A. T., & Wehner, E. H. 2002, AJ, 124, 1839
Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Richards, E. A. 2001, AJ, 121, 662
Barger, A. J., Cowie, L. L., Mushotzky, R. F., Yang, Y., Wang, W.-H., Steffen, A. T., & Capak, P. 2005, AJ, 129, 578
Barger, A. J., Cowie, L. L., & Richards, E. A. 2000, AJ, 119, 2092
Barger, A. J., et al. 2003, AJ, 126, 632
Bauer, F. E., Alexander, D. M., Brandt, W. N., Hornschemeier, A. E., Vignali, C., Fiore, F., & Schnei, D. 2004, AJ, 124, 2351
Bauer, F. E., Alexander, D. M., Brandt, W. N., Schneider, D. P., Treister, E., Elvis, M., et al. 2004, ApJS, 95, 1
Condon, J. J. 1989, ApJ, 338, 13
Cowie, L. L., & Moustakas, A. C. 1985, ApJ, 298, L7
Garmire, G. P., & Schneider, D. P. 2002, AJ, 124, 2351
Gillman, P., & Fabian, A. C. 2003, MNRAS, 339, 1095
Gronwall, C. 1988, ApJ, 328, 53
Hickox, R. C., & Markevitch, M. 2006, ApJ, 645, 95
Ivezic, Z., et al. 2002, AJ, 124, 2364
Kellermann, K. I., Snellen, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
Kuraszkiewicz, J. K., et al. 2003, ApJ, 590, 128
Lanzetta, K. M., Yahil, A., & Fernandez-Soto, A. 1996, Nature, 381, 759
Loose, M., Farris, M. C., Garnett, J. D., Hall, D. N. B., & Kozlovsky, L. J. 2003, Proc. SPIE, 4850, 57
Marcillac, D., Elbaz, D., Charry, R. Y., Dickinson, M., Galliano, F., & Morrison, G. 2006, A&A, 451, 57
Marshall, F., et al. 2000, ApJ, 235, 4
Martinez-Sansigre, A., Rawlings, S., Lacy, M., Fadda, D., Marleau, F. R., Simpson, C., Willott, C. J., & Jarvis, M. J. 2005, Nature, 436, 666
Monet, D. G., et al. 2003, AJ, 125, 984
Moran, E. C., Lehner, M., Lelend, D. J. J. 1999, ApJ, 526, 649
Mortari, A., Campana, S., Lazzati, D., & Tagliaferri, G. 2003, ApJ, 588, 696
Norman, C., et al. 2004, ApJ, 607, 721
Oke, J. B., et al. 1995, PASP, 107, 375
Pe´rez-Gonzalez, P. G., et al. 2005, ApJ, 630, 82
Petrella, M., et al. 2006, ApJ, 642, 673
Rahanni, P., Comastri, A., & Setti, G. 2003, A&A, 399, 39
Revnivtsve, M., Gilfanov, M., Jahoda, K., & Sunyaev, R. 2005, A&A, 444, 381
Richards, E. A. 2000, ApJ, 533, 611
Richards, E. A., Kellermann, K. I., Fomalont, E. B., Windhorst, R. A., & Partridge, R. B. 1998, AJ, 116, 1039
Risaliti, G., Maiolino, R., & Salvi, M. 1999, ApJ, 522, 157
Roeck H. D., Lowenthal, J. D., & Koo, D. C. 2002, MNRAS, 330, 307
Schechter, R., et al. 1979, Space Sci. Instrum., 4, 269
Sadler, E. M., et al. 2002, MNRAS, 329, 227
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, ApJ, 509, 103
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 728
Stocke, J. T., Morris, S. L., Weymann, R. J., & Foltz, C. B. 1992, ApJ, 396, 487
Swinbank, A. M., Smail, I., Chapman, S. C., Blain, A. W., Ivison, R. J., & Keel, W. C. 2004, ApJ, 617, 64
Szokoly, G. P., et al. 2004, ApJS, 155, 271
Teister, E., & Ury, C. M. 2005, ApJ, 630, 115
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 588, 886
Waddington, I., Windhorst, R. A., Partridge, R. B., Spinrad, H., & Stern, D. 1999, ApJ, 526, L77
Wang, W.-H., Cowie, L. L., & Barger, A. J. 2006, ApJ, 647, 74
White, R. L., et al. 2000, ApJS, 126, 133
Windhorst, R. A., Fomalont, E. B., Kellermann, K. I., Partridge, R. B., Richards, E. A., Franklin, B. E., Pascarelle, S. M., & Griffiths, R. E. 1995, Nature, 375, 471
Wirth, G. D., et al. 2004, AJ, 127, 3121
Worsley, M. A., Fabian, A. C., Barcons, X., Mateos, S., Hasinger, G., & Brunner, H. 2004, MNRAS, 352, L28
Worsley, M. A., et al. 2005, MNRAS, 357, 1281
Yu, Q., & Tremaine, S. 2002, MNRAS, 333, 965
Yun, M. S., Reddy, N. A., & Condon, J. J. 2001, ApJ, 554, 803
Zezas, A. L., Georgantopoulos, I., & Ward, M. J. 1998, MNRAS, 301, 915
Zheng, W., Kriss, G. A., Telfer, R. C., Grimes, J. P., & Davidsen, A. F. 1997, ApJ, 475, 469