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HIGH-FREQUENCY RADIO SPECTRAL ENERGY DISTRIBUTIONS AND POLARIZATION FRACTIONS OF SOURCES IN AN ATACAMA COSMOLOGY TELESCOPE SURVEY FIELD

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ABSTRACT

We present flux densities and polarization percentages of 159 radio galaxies based on nearly simultaneous Very Large Array observations at four frequencies, 4.86, 8.46, 22.46, and 43.34 GHz. This sample is selected from the high-frequency Australia Telescope 20 GHz (AT20G) survey and consists of all sources with flux density $S_{20\text{ GHz}} > 40$ mJy in an equatorial field of the Atacama Cosmology Telescope (ACT) survey. For a subset of 25 of these sources, we used the Green Bank Telescope (GBT) to obtain 90 GHz data. The goals of this program are: (1) a characterization of the spectra, polarization, and variability of high-frequency-selected radio sources, (2) extrapolating from the few GHz regime to the ~ 150 GHz regime of the ACT survey, allowing for more accurate removal of the radio source signal in our particular field, and (3) providing a data set that will allow more accurate modeling of the high-frequency radio source contamination in current and future Sunyaev–Zeldovich and cosmic microwave background experiments. We find that, as expected, this sample consists of flatter spectrum and more compact or point-like sources than low-frequency-selected samples. In the K band, variability is typically $\lesssim 20\%$, although there are exceptions. The higher frequency data are well suited to the detection of extreme gigahertz peak spectrum sources. The inclusion of the 43 GHz data causes the relative fraction of inverted spectrum sources to go down and of peaked spectrum sources to go up when compared with the AT20G survey results. The trend largely continues with the inclusion of the 90 GHz data, although $\sim 10\%$ of the sources with GBT data show a spectral upturn from 43 GHz to 90 GHz. The measured polarization fractions are typically $< 5\%$, although in some cases they are measured to be up to $\sim 20\%$. For sources with detected polarized flux in all four bands, about 40% of the sample, the polarization fractions typically increase with frequency. This trend is stronger for steeper spectrum sources as well as for the lower flux density sources.

Key words: galaxies: active – galaxies: jets – radio continuum: galaxies

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

1. INTRODUCTION

The high-frequency spectral energy distributions (SEDs) of radio galaxies are still poorly understood, in part because millimeter wave observations are more difficult than those at centimeter wavelengths (for a recent review see de Zotti et al. 2010). And yet, better characterization of these extragalactic sources, including their polarization properties, across a wider frequency range, will be invaluable for testing models of the physics of accreting black holes and radio jet formation. In addition to increasing our understanding of the physics of radio sources, knowledge of the high-frequency SEDs of foreground radio sources is becoming increasingly important as measurements of small-scale fluctuations in the cosmic microwave background (CMB) achieve higher sensitivity and higher resolution. The same is true for increasingly sensitive searches for the Sunyaev–Zeldovich (SZ) effect in clusters of galaxies. Radio sources both in clusters and in the field are a principal source of confusion in such experiments (see Lueker et al. 2010; Reichardt et al. 2009; Sharp et al. 2010; Sievers et al. 2009; Vieira et al. 2010; Fowler et al. 2010; Marriage et al. 2010).

The 10 m South Pole Telescope (SPT; Carlstrom et al. 2009) is conducting a survey for the SZ effect produced by clusters of galaxies (Staniszewski et al. 2009; Vanderlinde et al. 2010;

Lueker et al. 2010), and is also measuring small fluctuations in the microwave background. This group detects nearly 200 foreground sources, three quarters of which are dominated by apparent synchrotron radiation, with a small fraction, mostly faint sources, dominated by thermal dust emission (Vieira et al. 2010). The Atacama Cosmology Telescope (ACT) is carrying out a similar survey for the same purposes. Preliminary results reported by Marriage et al. (2010) at 148 GHz reveal more than 150, again mostly synchrotron, sources. In both cases, virtually all the detected sources are identified with radio sources contained in catalogs constructed at lower radio frequencies. And of course, the ongoing ESA *Planck* mission is conducting an all-sky CMB experiment over an unprecedented frequency range from 30 to 857 GHz (see, e.g., Tauber et al. 2010; Mandolesi et al. 2010; Planck Collaboration et al. 2011).

A better understanding of the high-frequency SEDs of foreground radio sources would permit a better statistical analysis of their effect on both the high- l power spectrum of CMB anisotropies and on increasingly sensitive surveys for the SZ effect. Data already available, for instance, suggest that the models of Toffolatti et al. (1998, 2005) based on extrapolations from lower frequency radio observations overestimate the effect of radio sources at millimeter wavelengths (Marriage et al. 2010).

High-frequency observations are particularly relevant to CMB observations made at frequencies of 90 GHz or above,

Table 1
Observation Summary

Band	Central Frequency (GHz)	Dates	Int Time (s)	Typical Sensitivity (mJy beam ⁻¹)	Configuration	Approximate Beam Size (arcsec)
<i>C</i>	4.86	2008 Jun 19–21	60	0.7	DnC	9 × 16
<i>X</i>	8.46	''	45	0.3	DnC	4.5 × 7.7
<i>K</i>	22.46	2008 Jul 25–Sep 6	60	0.9	D	3.1 × 4.4
<i>Q</i>	43.34	2008 Jul 17–Aug 8	330	1.2	D	1.7 × 2.1
<i>K</i>	22.46	2009 Nov 3–4	60	0.5	D	3.1 × 4.6
<i>Q</i>	43.34	''	300	0.6	D	1.6 × 2.4
<i>W</i>	90.0	2009 Dec	≥120	20.0	...	9
		2010 Jan	≥120		...	9
		2010 Mar	≥120		...	9

often to avoid signals from foreground sources. The polarization properties of these same sources at high frequencies are also of considerable interest given the current emphasis on polarization measurements in CMB research (see e.g., Battye et al. 2011). The characterization of polarized fluctuations in the CMB can help break some of the degeneracies between cosmological parameters, and hence can add to the accuracy of results obtained from the CMB temperature fluctuations. An example of this is the slope of the primordial perturbation spectrum. To constrain this quantity, polarization measurements at small scales are important, and it is at small scales that foreground sources have the maximum impact. The CMB polarization percentage at high l can reach $\sim 15\%$ – 20% ; a rough measure of the effect of polarized foreground fluctuations is the comparison of this number to the typical polarization percentage of high-frequency emission by extragalactic sources (Battye et al. 2011). Polarization of a source, and its dependence on the frequency of observation, also provides information about the physics of the emission process. For all these reasons, both SEDs and polarization measurements of foreground radio sources at high frequencies, equal to or approaching those used in current CMB studies, are of value. This paper addresses such observations. It parallels in some ways the earlier follow-up work on sources selected from the 15 GHz 9C survey of Waldram et al. (2003). In the follow-up work, Bolton et al. (2004) observed 176 sources at standard VLA frequencies, and obtained optical identifications for many of them. They do not, however, treat polarization.

This paper is organized as follows. In Section 2, we present the sample. In Sections 3 and 4, respectively, we discuss the Very Large Array (VLA) and Green Bank Telescope (GBT) observations and data reduction. In Section 5, we deal with the issue of the variability of sources. Section 6 presents our findings, including both polarization percentages and SEDs. We discuss the implications of our work with respect to millimeter-wave cosmology surveys, in particular the ACT survey, in Section 7. We summarize our conclusions in the final section. Throughout this paper, we adopt the Λ CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Spergel et al. 2003).

2. THE SAMPLE

The ACT survey includes two equatorial fields (both avoiding the Galactic plane) as well as a field centered on -53° declination, which is too far south for the VLA. In part as a service in support of ACT and the *Planck* mission, the Australia Telescope team (Murphy et al. 2010) extended the Australia Telescope 20 GHz survey (AT20G) of the southern sky up to the celestial equator. The AT20G survey thus covers one-half of the ACT's

equatorial strip, or about 30% of the total area of the ACT surveys. The AT20G survey limit is ~ 40 mJy. While the majority of sources in the AT20G catalog (Murphy et al. 2010) have follow-up observations at 5 and 8 GHz, that is not true of the sources at declinations north of -15° . Our observations were proposed to provide such low-frequency follow-up, but with the added benefit of extending the SEDs to higher frequencies as well. We selected all sources in the ACT equatorial regions that appeared in the preliminary version of the AT20G catalog. Slightly fewer than 200 sources fit the description, of which we have obtained observations for 159. Note that a couple of our targets which were in the preliminary version of the AT20G catalog were dropped from the final published version (Murphy et al. 2010). We did not observe every source in the survey area because telescope time was limited; however, the selection of those to omit from our survey was not based on flux or other properties of the source, but only on location. Thus, there should be no bias in the observed properties of our sample.

3. VLA OBSERVATIONS AND DATA REDUCTION

Measurements in all four spectral bands were made at default VLA frequencies, centered at 43.34, 22.46, 8.46, and 4.86 GHz. These are the *Q*, *K*, *X*, and *C* bands, respectively. The observations for the bulk of the sample were scattered over an interval from 2008 June 19 to September 6. For about one-third of the sample, the *Q*-band observations were made later on 2009 November 3 and 4. We also re-observed these sources in the *K* band in order to be able to estimate the level of variability between these two observing epochs (separated by 14–15 months).

For any given source, observations at the lowest two frequencies (*C* and *X*) were separated by no more than three days, and the observations for the highest two frequencies (*K* and *Q*) were made no more than 13 days apart. The observations discussed in this paper are summarized in Table 1.

The VLA was in a hybrid DnC configuration for the 2008 June 19–21 observations at the two lower frequencies, which were made first. Since the north–south baselines were on average longer than east–west baselines in this configuration, an elliptical synthesized beam resulted (see Table 1). For the later July–September observations at 22 and 43 GHz, the array was in its most compact D configuration. Thus, the synthesized beam size at 22 GHz was very roughly equal in the solid angle to the beam at 8 GHz. Because of work related to the transition to the EVLA, we typically had only 22–24 antennas available rather than 27, resulting in a 10%–20% reduction in sensitivity. The weather for these summer observations was mixed. Even though the observations were made in compact configurations

of the VLA, the scatter induced by atmospheric turbulence was clearly visible in the data. Most of the effects of turbulence were mitigated by self-calibration (see below).

In the case of observations at the two highest frequencies, we employed fast switching between the source of interest and a nearby, bright, phase calibrator source. The integration times on source and calibrator were set to be approximately equal to or less than the atmospheric phase coherence time at 43 GHz. For the *K* band, the integration times were 60 s on the source and 30 s on the calibrator. For the *Q*-band observations, we used 110 s on the source and 40 s on the calibrator. Given the relatively low sensitivity of the *Q*-band receivers, we repeated that cycle three times for each source at *Q* band. The integration times of the source listed in Column 4 of Table 1 give approximate values for each band.

Roughly 70 of our sources did not get observed at 43 GHz as planned in the summer and early fall of 2008 (that is, during the first round of observations). Both weather and scheduling problems got in the way. The sources omitted were those in the right ascension range $04^{\text{h}}08^{\text{m}}$ to $13^{\text{h}}22^{\text{m}}$. In a second application to NRAO, we received additional time for follow-up observations on 2009 November 3–4 to complete our catalog. Again, time limitations prevented us from observing all 70 sources, but all the 58 sources that we did observe at 43 GHz, we also re-observed at 22 GHz to allow us to assess the level of variability of these sources between the two observing epochs (2008 September and 2009 November). The integration times for these follow-up runs, conducted in the most compact D configuration, amounted to roughly 1 minute in the *K* band and 5 minutes in the *Q* band for each source (see Table 1).

3.1. Data Reduction and Calibration

The data reduction was done using the standard VLA package AIPS (Automatic Image Processing Software⁷). In each band, the raw amplitude and phase data were flagged for shadowing of one antenna by another, interference, noisy correlators, malfunctioning antennas, and so on. In general, this flagging process removed only a few percent of the raw data. Corrections for baseline errors in the array were applied. Since all of our sources are quite bright, we were able to use self-calibration to improve the phases of our UV data, with the exception of six faint sources at 43 GHz. All our images, and consequently all of the flux densities, are determined from self-calibrated data, except for the six weakest *Q*-band sources as mentioned above. We corrected for elevation-dependent atmospheric absorption using standard VLA procedures and values in each band. In the *K* band, the typical value of zenith extinction was 0.07–0.11 for the summer 2008 observations and 0.07 for the 2009 November observations.

The flux density scale was fixed by observing one or both of two standard NRAO flux calibrators, 0137+331 (3C48) or 1331+305 (3C286), during each observing run. For 0137+331, we employ the standard NRAO flux densities of 5.4320 Jy, 3.1543 Jy, 1.1188 Jy, and 0.5297 Jy for the *C*, *X*, *K*, and *Q* bands, respectively. Our measured flux densities, taken from our images of these sources, are 5.415 ± 0.010 , 3.154 ± 0.013 , 1.122 ± 0.004 , and 0.528 ± 0.005 Jy for the same four bands. For 1331+305, the standard NRAO flux densities are 7.486, 5.2053, 2.5192, and 1.4555 Jy; we measured 7.474 ± 0.030 , 5.215 ± 0.020 , 2.507 ± 0.017 , and 1.470 ± 0.014 Jy. A variety of secondary, phase calibrators near our equatorial regions were

observed frequently (and were used for fast switching for the *K*- and *Q*-band observations).

Each source in each frequency band was imaged using standard AIPS procedures. In this process, we selected a pixel size for each frequency band to fully sample the synthesized beam size (\sim angular resolution) at that frequency. These were $2''$, $1''$, $0''.3$, and $0''.15$ for the *C*-, *X*-, *K*-, and *Q*-band images, respectively. In all cases, we constructed 1024×1024 images. In most cases, the raw images of sources were lightly cleaned of interferometric side lobes using standard NRAO procedures in AIPS. The exceptions to this procedure were the 26 clearly resolved or multiple sources; these images required heavier cleaning (in some cases, up to 2000 clean components were removed). We experimented with different levels of cleaning, and found no significant change in the flux densities of the unresolved sources, or unresolved components of more complex sources.

3.2. Flux Densities

For the 133 sources that are not resolved, or barely resolved, we use the standard AIPS program IMFIT to fit a two-dimensional Gaussian to the image, and to derive the integrated flux density and its associated uncertainty (which includes the rms of the image and the fit uncertainty). In addition, we estimate calibration uncertainties from the scatter in values from different measurements of VLA calibrators made during our runs. These are: 1.0% for the *C*- and *Q*-band measurements, 0.8% for the *K* band, and 0.7% for the *X*-band measurements. The error associated with each measurement of the total flux density is the quadrature sum of the IMFIT error and the uncertainty in the overall flux scale in each frequency band. Given the high signal-to-noise ratios, the calibration uncertainty term dominates. The integrated flux densities and these total errors are the values given in Table 3.

The situation for the 26 resolved sources shown in Figure 1 is more complicated, and often frequency dependent. For many sources, at least at some frequencies, a bright unresolved or barely resolved core is clearly visible (e.g., J075447–024734). Flux densities of these cores are denoted by *C* in Column 2 of Table 2. These flux densities were obtained using IMFIT and a tight-fitting box around the core. To obtain the total fluxes at each frequency, we marked a large box enclosing all visible emission and then used the AIPS program IMSTAT to compute the total flux. These total flux densities are denoted by “*T*” in Column 2 of Table 3. Both the values and the errors of the total flux for such sources should be used with care, since flux was almost certainly being resolved out.

3.3. Polarization Calibration and Flux Densities

Our observations were typically made in short time intervals (a couple of hours). Most sources (including calibration sources) were observed near the meridian. For both reasons, the change in the parallactic angle of potential polarization calibrators, such as 1331+305 and 0137+331, was small. Consequently, we use the known polarization fraction and polarization angle of these sources to make an approximate determination of the leakage and R–L phase difference from single scans, which we then apply to the rest of the data. Normally, use of polarized sources for polarization calibration requires two or three scans (if source polarization is unknown) at different parallactic angles in order to break the degeneracies between source and instrumental polarization. Our procedure uses a step in the calibration where

⁷ <http://www.aips.nrao.edu/cook.html>

Table 2
Calibrator Polarization Percentage

Source	C Band		X Band		K Band		Q Band	
	% Prior	% This Paper	% Prior	% This Paper	% Prior	% This Paper	% Prior	% This Paper
NRAO								
0137+331	4.1	4.6	5.5	5.9	8.0	9.6	8.9	9.5
1331+305	11.3	11.5	11.8	11.9	11.7	12.5	11.3	14.5
J042315–012033 ^b	1.37 ± 0.03	1.1 ± 0.1	1.23 ± 0.05	2.6 ± 0.2	1.44 ± 0.05	3.0 ± 0.3	2.31 ± 0.21	2.0 ± 0.2
AT20G								
J000622–000423					2.6	2.8 ± 0.5		
0725–009 ^a					1.4	0.6 ± 0.1		
J074554–004418					3.5	4.0 ± 0.4		
1150–003					2.6	1.3 ± 0.2		
2134–018					7.4	7.6 ± 0.8		
J220643–003103 ^b					6.5	<4.4		
J230107–015804					5.2	7.6 ± 0.8		

Notes.

^a The value given is for the 2009 November observations. For the 2008 September 6 observations (where the polarization calibration is highly uncertain), we find 2.7 ± 0.5 for this source.

^b This is a strongly variable source.

Table 3
Flux Densities and Polarization Percentages^{a,b}

Source	Flag ^c	z	S_C (mJy)	S_X (mJy)	S_K (mJy)	S_Q (mJy)	p_C (%)	p_X (%)	p_K (%)	p_Q (%)	Class
J000507–013244		1.710	38.9 ± 0.5	48.7 ± 0.4	57.6 ± 1.1	52.1 ± 1.5	3.1 ± 0.9	4.1 ± 0.9	<11.2	<9.08	GPS
J000622–000423		1.037	1343.7 ± 14.	830.2 ± 6.0	305.4 ± 3.3	145.5 ± 2.3	2.7 ± 0.3	2.9 ± 0.2	2.8 ± 0.5	4.44 ± 1.4	
J001611–001511		1.575	491.0 ± 5.8	383.5 ± 2.7	259.7 ± 2.8	231.7 ± 2.7	1.4 ± 0.2	.84 ± 0.1	1.5 ± 0.5	2.6 ± 0.8	
J001752–023618			59.5 ± 0.7	62.5 ± 0.5	69.0 ± 1.2	82.1 ± 1.3	3.8 ± 0.7	3.1 ± 0.5	9.43 ± 1.8	14.6 ± 3.5	Inverted
J001917–010357	C		65.9 ± 0.9	66.0 ± 0.5	66.0 ± 1.4	61.6 ± 1.2	1.4 ± 0.4	<1.26	<14.4	<10.7	GPS
	T		84.0 ± 2.2	85.5 ± 1.2	66.0 ± 1.1	61.0 ± 1.2					
J002336–025307			156.2 ± 1.7	103.6 ± 0.8	45.6 ± 1.0	30.0 ± 1.1	1.0 ± 0.2	2.1 ± 0.4	8.53 ± 2.5	<16.5	
J002901–011341		0.086	249.9 ± 2.7	231.9 ± 1.6	167.7 ± 1.8	127.2 ± 1.4	3.2 ± 0.3	2.4 ± 0.2	2.88 ± 1.0	<5.43	
J003007–000007		0.475	82.0 ± 0.9	79.0 ± 0.6	61.2 ± 1.1	51.2 ± 1.1	<2.03	1.1 ± 0.4	6.74 ± 2.3	<9.00	
J003031–021156			279.1 ± 3.0	231.8 ± 1.6	123.9 ± 1.6	88.9 ± 1.4	2.5 ± 0.2	2.8 ± 0.2	<4.45	<8.16	

Notes.

^a The quoted uncertainties are the quadrature sum of the AIPS IMFIT fitting uncertainty (which is typically slightly larger than the rms) and our estimated systematic uncertainty. For the flux densities the flux calibration uncertainty is equal to 1% for the C band, 0.7% for the X band, 0.8% for the K band, and 1% for the Q band. For the polarization percentages, we estimate an uncertainty (based on the measured spread in the polarization of our calibrator sources) of 8% in the C band, 10% in the K band, and 8% in the Q band.

^b The bulk of these data were taken in the summer and early fall of 2008 (see Table 1). For the subset of sources with K- and Q-band observations in 2009 November, these flux densities and polarization percentages are listed just below the 2008 values for the same source.

^c C = core, J = jet, T = total. The jet (or lobe) photometry is quoted for J094123–014251, since for this source the northern jet corresponds to the AT20G position (see Figure 1).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

the first-order antenna-based leakage terms average to zero over the array.⁸ This procedure was carried out using the CASA software package (<http://casa.nrao.edu>). In order to break these degeneracies and get a viable solution. However, this procedure will leave a small residual of the calibrator polarization in the leakage solutions, which will lead to an overall offset to the derived source polarizations (e.g., a small bias in polarization) that should be factored into the interpretation of these results.

Because of the residual polarization biases described above, our procedure is not as accurate or robust as using observations of the same source that spans a range of parallactic angles. Therefore, we carry out a number of tests. First, we compare our values of the total polarized flux for a few calibrators to

those tabulated in polarization calibration tables maintained at the NRAO.⁹ This is shown in the upper half of Table 2. For 0137+331 and 1331+305, our primary flux calibrators where we have multiple observations, we show both the average value of our observations and the average of the NRAO-tabulated values closest in time to our observations. For J042315–012033, we used the 2008 January 13 tabulated measurement for the C and X bands and the 2009 December 14, measurement for the K and Q bands. Note, however, that this source is strongly variable, as we discuss in Section 6.5. The only other calibrator source which we observed and is monitored by the NRAO is 2136+006. However, this source was only observed in the K band and showed a messy/extended structure. However, for comparison, the NRAO observation of 2008 July 28 gives its

⁸ Actually, we assume that the average of $d_{iR} + d_{iL}^*$ is zero over the array. See the CASA Manual for details on polarization calibration.

⁹ <http://www.vla.nrao.edu/astro/calib/polar/calsources.shtml>

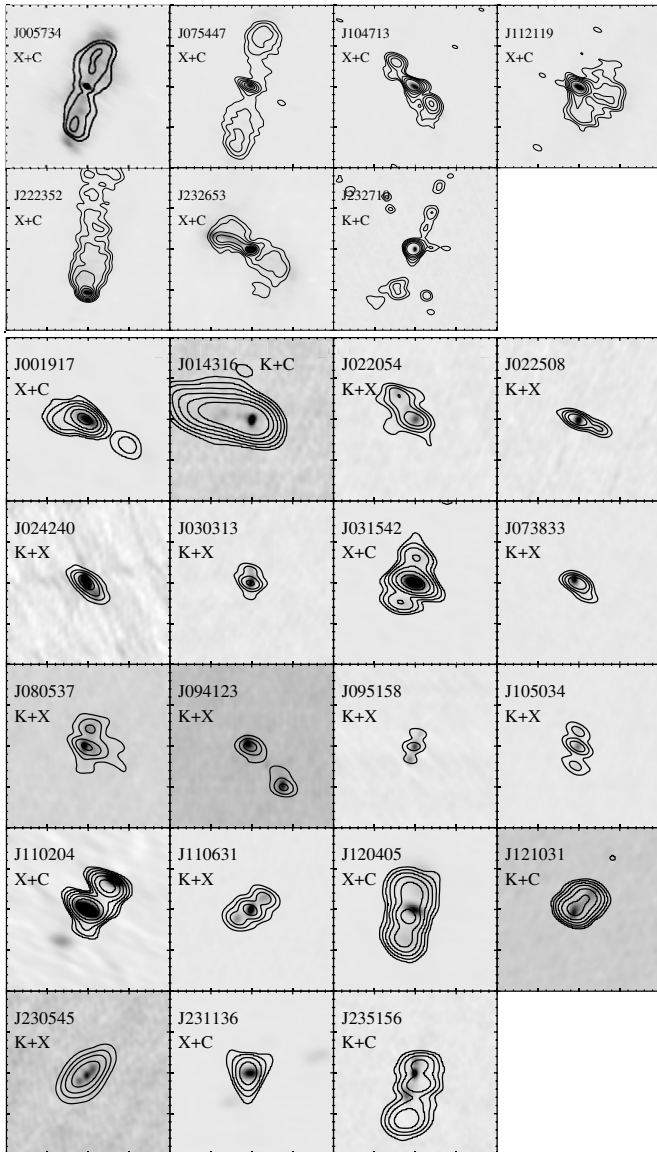


Figure 1. Images of the 26 sources resolved at one or more of our frequencies. The images are not all to the same scale. In each case the gray-scale image is taken from the higher resolution (higher frequency) image, and the contours from the lower resolution image of the same source. Which two frequency bands are imaged is indicated in each panel. For source J005734, for instance, the gray-scale image is the X-band (8 GHz) image; the contours are shown from the C-band (5 GHz) image.

K-band polarization as 2.5 ± 0.1 , while we find 4.2 ± 1.3 from our 2008 July 25 observations. With the exception of our Q-band measurement for 1331+305, the agreement for the two primary calibrators is acceptable. However, there is an evident trend for our polarized flux densities to run a few percent high, as expected for our polarization calibration procedure, but we do not attempt to correct our values for this trend. In Table 2, we also compare polarization percentages for a few of the sources with measured polarizations in the AT20G survey (Murphy et al. 2010). Bearing in mind the possibility of variability, we again see reasonable agreement for these few sources. In light of the discussion in Section 5.2, we note explicitly that we compare polarization percentages with the AT20G data, and not polarized flux.

Here, we discuss only the linear polarization component. While the study of circular polarization is beyond the scope

of this paper, we did look at the Stokes V images for a small number of sources, including all those showing $>10\%$ linear polarization in a given band. In all cases, we found that the circular polarization percentage is consistent with being $\lesssim 1\%$.

We use IMFIT to measure the integrated flux densities (S_Q , and S_U) and their uncertainties (σ_Q and σ_U) from the Stokes Q and U images. This was done even if no polarized flux was visible (in Section 3.4 we discuss the determination of the linear polarization fraction including upper limits). For extended sources, we measure the polarization of the core only. The IMFIT fitting box was determined from the Stokes I images and then kept fixed for the much smaller signal-to-noise Stokes Q and U images. We skip sources at a given frequency where the core is not clearly defined. In a small number of cases, IMFIT failed, and we used the AIPS program IMSTAT to estimate the polarized flux within our fitting box. We look at the spread in Stokes Q and U values in a few cases of multiple observations of the same calibration source. Combined with the results of Table 2, these suggest systematic uncertainties in the value of polarized flux densities of $\sim 8\%$, 6% , 10% , and 8% in the C, X, K, and Q bands, respectively. As in the case of the Stokes I flux, these internal uncertainties were combined in quadrature with the IMFIT errors. Unlike the case for Stokes I, this calibration uncertainty dominates the error budget only for the brightest or most strongly polarized sources.

3.3.1. Problematic Polarization Calibration

Two of the twelve batches of data (one K band and one Q band) presented problems with polarization calibration. These are addressed in turn below.

The 2008 July 17, Q-band observations (R.A. range 19–23:50 hr) were done in particularly bad atmospheric conditions, and hence required more aggressive flagging. As a consequence, the statistical errors in both total intensity and polarized flux are larger than for other data sets. In six cases, the data do not provide reliable polarization fluxes. The 2008 July 17 Q-band data are also not baseline calibrated, unlike other data. We found that removing the baseline calibration for this data set gave more reasonable polarization fractions for the calibrators, although of course the total intensity values were then wrong (we use the baseline calibrated data only to get the Stokes I values). Because of the poor quality of this batch of data, the Q-band polarization fractions for these sources are typically upper limits, with only the highest polarization fractions being detectable.

Using the polarization calibration procedure described above, our first attempt at polarization calibration of the 2008 September 6 K-band data failed. While the total intensity values were reasonable, there was a factor >2 error in the polarization percentages for calibrators with known polarization. These data include sources in the R.A. range 07–13 hr, which set of sources were re-observed in 2009 November. As the 2009 November data were taken in significantly better weather (and higher instrumental sensitivity), and moreover were near-simultaneous with the Q-band data for the same sources, we mostly use the later observations in our analysis. We tried two different solutions to this. First, we used the raw Stokes Q and U images to obtain polarized flux densities. With no allowance for instrumental polarization, the polarization angles derived in this way make no sense, but given both small polarization fractions of our sources and small instrumental polarization of the VLA antennae, the quadrature sum of the Q and U images should give a reasonable representation of the total polarized flux. We test this

by comparing our 2008 September K -band polarization fractions with the 2009 November K -band polarization fractions for the same sources. We find a median ratio of 1.14 with significant scatter. On the other hand, the bright calibrators show a median ratio of 0.83. Excluding upper limits, $\sim 12\%$ of these sources have polarizations that are a factor of two higher in 2008 than in 2009. All of these, also show strong variability in their Stokes I flux densities. The apparent one-sidedness of the variability can be understood when we consider the significantly different sensitivities of the two data sets. A source whose polarization fraction grows from 2008 to 2009 would almost certainly appear as an upper limit in the 2008 data. The sources, whose polarization fraction changes significantly between the two epochs are: J073025–024125, J073245–022858, J091643–025910, J102834–023659, and J111439–024731. However, due to the problematic polarization calibration it is hard to judge whether these are scientifically interesting or merely reflect the poor quality of the September 6 K -band data set.

We were later able to use the new NRAO data reduction package, CASA, to repeat the polarization calibration of this data set, but without the standard baseline calibration (as in the case of the 2008 July 17 Q -band data). The comparison between the values obtained above and these new polarization fraction values then showed a ratio between the two of ~ 1 after three outliers with $>50\%$ variability were excluded. These were all revealed to be extended sources, which we did not account for in the CASA reduction. Apart from such outliers, the scatter is largely consistent with the quoted errors. Because of this good agreement and the more careful treatment of extended sources in our earlier reduction, we decided to stick with the values obtained from the raw Stokes Q and U images, but note that performing polarization calibration on the data without baseline calibration yielded consistent answers.

3.4. Estimating the Degree of Linear Polarization

Here, we largely follow the prescription of Simmons & Stewart (1985), with the exception that we do not equate σ_q and σ_u (see also Topasna 1999 for an extended discussion). We begin by defining the normalized Stokes parameters: $q = S_Q/S_I$ and $u = S_U/S_I$, where S_I is the Stokes I (i.e., total) flux density. The uncertainties on q and u , σ_q and σ_u , respectively, can be computed from the measured flux density errors by using the following expressions:

$$\sigma_q = q \sqrt{\left(\frac{\sigma_Q}{S_Q}\right)^2 + \left(\frac{\sigma_I}{S_I}\right)^2}, \quad \sigma_u = u \sqrt{\left(\frac{\sigma_U}{S_U}\right)^2 + \left(\frac{\sigma_I}{S_I}\right)^2}. \quad (1)$$

The measured degree of linear polarization, p , is then given by

$$p = (q^2 + u^2)^{1/2}. \quad (2)$$

Assuming that the errors on q and u are independent, the uncertainty on p is given by

$$\sigma_p = \frac{1}{p} \sqrt{q^2 \sigma_q^2 + u^2 \sigma_u^2}. \quad (3)$$

It is well known that this expression (Equation (2)) is inherently biased as $p > 0$ even if there is no true linear polarization, due to the presence of noise on S_Q and S_U . Using σ_p defined in Equation (3), the bias correction takes the form

$$p_{\text{corr}} = \sqrt{p^2 - (K \sigma_p)^2}, \quad (4)$$

where K is the bias correction factor. Note that, p_{corr} is only defined where $p > K \sigma_p$. Simmons & Stewart (1985) compare several different approaches to estimate K . For cases where $p/\sigma_p > 0.7$, they advocate the Wardle & Kronberg estimator with $K = 1$. For lower signal-to-noise ratios, the recommended value is $K = 1.41$ based on the maximum likelihood estimator of the true value of p . In practice, all our quoted polarization percentages are based on $K = 1.0$. In Table 3, we quote the linear polarization percentages, i.e., $100 (p_{\text{corr}} \pm \sigma_p)$. Note also that our quoted σ_p likely represents a confidence level close to but somewhat less than 68%. This difference is not crucial for our purposes and hence for simplicity it is ignored. In order to assess whether or not a given source can be considered to have detectable polarization, we also look at the associated confidence intervals. Simmons & Stewart (1985) provide a procedure for estimating these, but also quote conservative estimates based on the assumption that p^2 is χ^2 -distributed. This assumption leads to a 68% confidence level of $[\max(0, p - 1.49\sigma_p), p + 1.49\sigma_p]$ and a 95% confidence level of $[\max(0, p - 2.45\sigma_p), p + 2.45\sigma_p]$. Note that Simmons & Stewart (1985) argue that these are somewhat larger than the true confidence intervals (by roughly 20%–40%), and hence are a fairly conservative choice. We take any source with a 95% lower confidence level of zero to be a non-detection. In such cases, Table 3 shows the 95% upper limit (i.e., $p + 2.45\sigma_p$). Sources detected in only one of Stokes Q or U still have an overall polarization percentage detection, while the upper limits on p are typically associated with sources without a significant detection in either Q or U .

4. GBT 90 GHz OBSERVATIONS AND DATA REDUCTION

For 25 of our sources, we also obtained flux measurements at 90 GHz using the MUSTANG receiver (Dicker et al. 2008) on the 100 m diameter GBT. MUSTANG is a 64 element array of TES (transition edge sensor) bolometers with a bandpass of 81–99 GHz. On the GBT, it has a beam FWHM of $9''$ and detectors are spaced by $0.7f\lambda$ to give a field of view of $45''$ square.

Our observations were carried out in three night time sessions. Observing at night is necessary as during the day solar heating distorts the shape of the GBT’s primary mirror causing significant gain changes on timescales faster than that can be calibrated out (15 minutes or less). At the start of each session, Out-of-focus (OOF) holography was used both to find the focus and to measure the pointing offsets and residual large-scale thermal distortions of the mirror (Nikolic et al. 2007). The thermal distortions were then compensated for using the GBT’s active surface. This procedure increases the forward gain of the telescope and hence the signal to noise by 10%–30%.

Each source was observed at least twice using 60 s “daisy petal” scans which modulate the source position on the array faster than drifts in any detector. Most sources were easily detected in a single scan, but observing twice provided a consistency check and allowed better determination of our errors. Quick look software was used to check for clear source detections and more scans taken if needed. Observations of an absolute calibrator were carried out every 20–30 minutes. In the first session, our calibrator was Mars, and in the second, Saturn, supplemented by the secondary calibrator 1058+0133 which was nearer to our sources. In the final session, we used Ceres and Neptune. After observing each calibrator, a short data file was taken while pulsing MUSTANG’s internal blackbody calibrator; “CAL.” The amplitude of this response is used to calibrate the optical response of each bolometer.

Data analysis was carried out by making maps of each source and individual calibrator observations. First, the response of each detector was normalized by its response to “CAL” and dead or noisy detectors were flagged. This timestream data are dominated by emission from the atmosphere, the telescope, and MUSTANG’s internal optics which are all highly common mode between pixels. Thus, by fitting a common mode signal to all off-source pixels the majority of atmospheric and instrumental signal is removed. In addition, we explicitly fit and remove a 1.4 Hz sine wave (caused by internal temperature fluctuations in the receiver) and subtract a baseline from the timestream of each detector which has timescales longer than the modulation of the source (typically 0.5 Hz). The data are then binned in elevation/cross-elevation.

To convert from our arbitrary units of “CALs” to Janskys, the following steps were carried out.

1. Gaussian fits to each map were used to obtain the source amplitudes (in “CALs”) and also to find the solid angle of the GBT’s beam as a function of time.
2. The opacity as a function of time was calculated using the observing tools at Green Bank.¹⁰ These tools make use of pressure, temperature, and humidity profiles of the atmosphere measured by the National Weather Service.
3. The expected brightness of the planets (in Jy) was calculated assuming the blackbody temperatures in Weiland et al. (2011) and Wright (2007), angular diameters from the Horizons ephemeris,¹¹ the measured beam sizes, and the measured 18 GHz bandpass of MUSTANG.
4. For each observation of a calibrator, the conversion of “CALs” to Janskys was calculated and these values extrapolated to the observation of each source.

The 90 GHz flux densities with their associated 1σ uncertainties of our 25 GBT targets are presented in Table 4.

5. VARIABILITY

We had two means of detecting variability in the flux density of our sources: comparison of our 22 GHz measurements with the AT20G survey from which we drew our sample and comparison of the 22 GHz fluxes of the 58 sources observed in the summer of 2008 and then re-observed in early 2009 November. We refer to the latter as the internal comparison.

5.1. Variability Detected Internally in Our VLA Measurements

Figure 2 (top) shows a comparison of the K -band fluxes for sources that were observed both in 2008 and again in 2009 November. The 2009 measurements were made in better weather, so any decoherence caused by atmospheric turbulence should affect the 2008 values more. Instead, we find marginal evidence that the 2009 November flux densities were on average slightly lower once we had flagged and removed some manifestly variable sources. We find a median offset of 7% with a standard deviation of 21%. Of the 45 point-like sources we observed in the K band in both epochs, two have varied by more than 50%.

We estimate the variability index of each source following the prescription in Sadler et al. (2006). We include only our own VLA K -band flux density measurements. The second panel of Figure 2 shows a histogram of the K -band variability indices for our sources, where available. We get a median

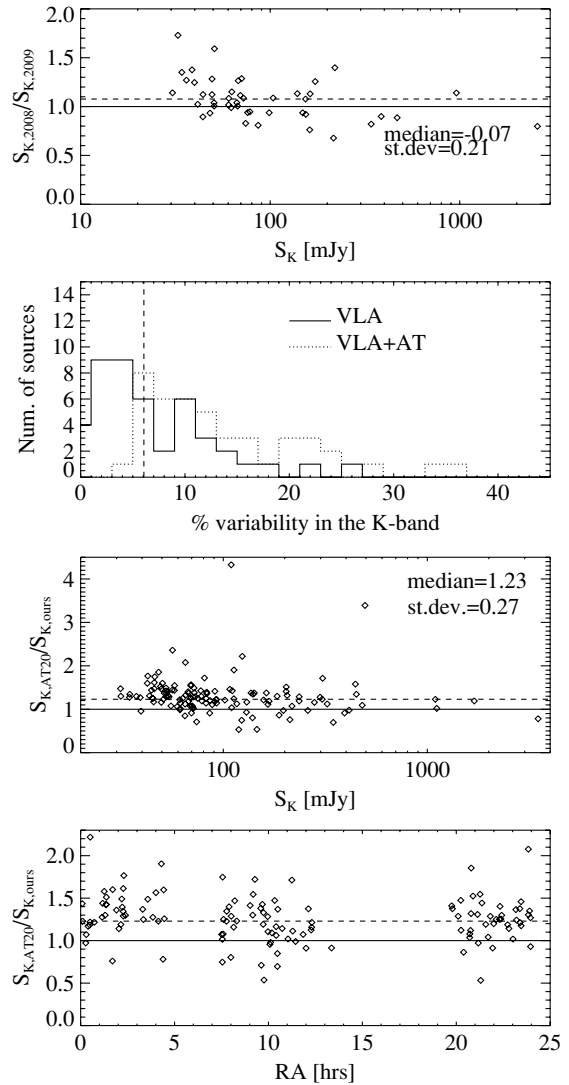


Figure 2. Top panel shows the ratio of the two epochs of VLA K -band flux estimates as a function of K -band flux (from 2009 November). The second panel shows the variability index based on the VLA data alone (solid histogram), and based on the VLA+AT data (dotted histogram). The dashed line shows the median variability based on the VLA data alone. The third panel shows the ratio of the AT20G fluxes and our K -band fluxes of unresolved sources, after correction for difference in effective frequency. The bottom panel shows what appears to be a dependence on R.A., suggesting some systematic effects might also be at play. For clarity, this figure excludes J220643+003103 which has a ratio of 4.4 (see the top panel). The dashed lines in both panels show the median ratio.

value of 6.1% (dashed line in Figure 2), which is slightly lower than but still compares well with the median value of 6.9% found in a follow-up in the K band of 170 of the AT20 sources (Sadler et al. 2006; Murphy et al. 2010). Bolton et al. (2006) find a median variability for their 15 GHz-selected sample of $\sim 7.2\%$, but classify only 29% of sources as clearly variable above their flux density uncertainty of $\sim 6\%$. Figure 2 also shows the variability index histogram obtained when we include the AT20G K -band flux densities as well, where we have corrected for the effective frequency difference and have divided the AT20G fluxes by the median offset we discover in Section 5.2.

5.2. Comparison with AT20G

The majority of the AT20G flux densities at 19.904 GHz reference frequency (Murphy et al. 2010) were determined in

¹⁰ For details see <http://www.gb.nrao.edu/~rmaddale/Weather/>.

¹¹ Available at <http://ssd.jpl.nasa.gov/horizons>.

Table 4
90 GHz Measured and Extrapolated Fluxes

Name	$S_{90 \text{ GHz, meas}}$ (mJy)	$S_{90 \text{ GHz, extrap}}$ (mJy) VLA S_K	Ratio	$S_{90 \text{ GHz, extrap}}$ (mJy) $S_K \times 1.24$	Ratio
J021542–022256	112.4 ± 18.8	181.9	0.6	143.2	0.8
J041758–025019	114.3 ± 19.2	67.2	1.7	52.9	2.2
J042315–012033	5982.8 ± 966.8	7062.3	0.8	5560.3	1.1
J073025–024125	109.5 ± 18.3	118.5	0.9	93.3	1.2
J073245–022858	65.7 ± 11.0	79.7	0.8	62.7	1.0
J074554–004418	373.6 ± 60.8	362.5	1.0	285.4	1.3
J075953–022803	125.2 ± 21.0	131.7	1.0	103.7	1.2
J080512–011114	101.7 ± 17.1	33.9	3.0	26.7	3.8
J094544–015304	104.7 ± 17.0	193.7	0.5	152.5	0.7
J100445–011917	13.4 ± 2.4	51.2	0.3	40.3	0.3
J100704–020711	189.1 ± 27.8	361.2	0.5	284.4	0.7
J102834–023659	614.1 ± 90.2	1224.9	0.5	964.3	0.6
J104341–014407	26.4 ± 4.2	76.1	0.3	59.9	0.4
J111439–024731	141.4 ± 20.8	225.0	0.6	177.2	0.8
J120741–010630	217.5 ± 31.9	211.2	1.0	166.3	1.3
J121622–010753	67.1 ± 9.9
J121758–002945	556.7 ± 81.7	601.3	0.9	473.4	1.2
J121834–011953	81.0 ± 11.9	121.7	0.7	95.8	0.8
J202332–012341	201.0 ± 15.9	168.9	1.2	133.0	1.5
J211807–025847	72.1 ± 6.1	87.5	0.8	68.9	1.0
J215614–003704	497.1 ± 39.3	347.1	1.4	273.3	1.8
J230107–015804	303.0 ± 24.2	941.8	0.3	741.5	0.4
J232304–015048	139.7 ± 11.2	236.6	0.6	186.3	0.8
J232653–020213	215.1 ± 17.1	120.2	1.8	94.6	2.3
J235725–015214	53.4 ± 4.5	95.6	0.6	75.3	0.7

Table 5
Mean and Median^a Spectral Indices

Subset	α_{CX}	α_{XK}	α_{KQ}	α_{QW}
Singles	−0.16(−0.13)	−0.37(−0.35)	−0.45(−0.41)	
Singles+total	−0.24(−0.21)	−0.43(−0.37)	−0.49(−0.45)	
90 GHz sample	0.07(0.03)	−0.06(−0.09)	−0.14(−0.09)	−0.47(−0.46)

Note. ^a The number in parentheses is the median.

2007 October, that is roughly 10 months before our K -band observations began. The AT20G flux densities for the point sources in our sample are plotted against our measurements in Figure 2. Some sources are evidently strongly variable. The most salient example is J220643–003103, for which we measure a flux $< 1/4$ of that found earlier by the Australia Telescope.

In addition to evidence for variability, we found a systematic difference in flux densities, in the sense that our flux densities on average tended to be lower than those measured earlier at the Australia Telescope. Some of the difference is due to the different center frequencies used in the two surveys, 22.46 GHz for our VLA work and 19.90 GHz for the AT20G survey. To make a first-order correction for this effect, we used the spectral indices we determined between 8.46 and 22.46 GHz to interpolate our flux densities to the AT20G frequency. It is these interpolated values that we plot in Figure 2. We were also concerned that our measurements at the VLA, made with antenna spacings as large as ~ 1 km, could be missing some flux as a consequence of resolution effects. We thus excluded from Figure 2 and the remaining discussion the 26 sources that were evidently resolved or showed structure in any of our observations. Whenever available, the 2009 November K -band fluxes are used, as generally those data were of better quality.

After all these steps and after we exclude the strongest outliers, the median ratio is $S_{AT, 19.9 \text{ GHz}}/S_{VLA, 19.9 \text{ GHz}} = 1.23$

with a standard deviation of 0.27. The mean ratio is 1.19 ± 0.02 . We note that such an offset was first reported for a small number of VLA calibrators in Murphy et al. (2010) where they find a median AT20G/VLA ratio of 1.08 ± 0.10 . This ratio is smaller than we find here; however, their comparison is done for calibrator (hence, higher flux density) sources. Therefore, the first test we perform is to look at the median ratio of bright sources in our sample. In order to have reasonable numbers, we select > 200 mJy as the criterion for a “bright” source. With this flux density cutoff, we find a median ratio of 1.16 and an rms of 0.28. Figure 2 also shows the ratio with respect to R.A. The dashed line shows the median ratio for the full sample (i.e., 1.23). We note that sources in the R.A. range 0–5 hr show particularly high ratios that are nearly always above the median for the sample (this may extend up to R.A. ~ 9 hr). If we look at R.A. > 5 hr sources only, we find a median ratio that drops significantly to 1.14 ± 0.04 where the error is rms/\sqrt{N} . We can make the further restriction of looking at bright sources at R.A. > 5 hr. There are only nine such sources, but the median ratio has now dropped to 1.07 ± 0.11 . We note that our K -band data for R.A. ~ 20 –5 hr sources were all taken on the same day (2008 July 25; see Table 1), and were subjected to the same setup, atmospheric conditions, and subsequent data reduction. Therefore, it is unlikely that there is a systematic difference between the flux scale we measure for the R.A. = 0–5 hr and

R.A. = 20–24 hr sources. We note that the AT20G survey is at its noisiest in the equatorial strip where we overlap, and therefore it is not clear that this flux density offset necessarily would translate to an overall offset between the flux density scales of ATCA and the VLA. Our K -band fluxes are fully consistent with the absolute flux scale of the VLA at that frequency as can be seen by the flux densities for both the primary and secondary calibrators we observe (see Section 3.1).

Murphy et al. (2010) quote a comparison with the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) fluxes yielding a mean value of $\langle (S_{\text{AT20G}}/S_{\text{WMAP}}) \rangle = 1.01 \pm 0.03$. This is based on very bright sources ($S_{\text{AT20G}} \gtrsim 500$ mJy). We do not have enough sources in this flux range for good statistics. We can, however, compare some individual bright sources in our sample with the seven year, five band *WMAP* point source catalog (Gold et al. 2011). The calibrator source 0725–009 has $S_K = 1.99$ Jy which is sufficiently different from the $S_{K,\text{WMAP}} = 1.0$ Jy to suggest variability is at play. On the other hand, 1150–003 has $S_K = 0.803$ Jy which is very close to the $S_{K,\text{WMAP}} = 0.8$ Jy, while 2134–018 has $S_K = 1.73$ Jy which is about 11% lower (after accounting for the difference in central frequency and the spectral index) than the $S_{K,\text{WMAP}} = 2.0$ Jy. Other bright sources such as J042315–012033 and J074554–004418 are not useful here as they show too strong a variability, while J230107–0158804 was not found in the *WMAP* catalog. Finally, we can look at the two primary calibrators we use, 0137+331 ($S_{K,\text{WMAP}} = 0.9$ Jy) and 1331+305 ($S_{K,\text{WMAP}} = 2.3$ Jy). In both cases, our K -band flux densities are actually larger, in the case of 0137+331 by $\sim 20\%$. From so few sources it is difficult to draw conclusions, but these values suggest that, for bright sources, there is no evidence that our VLA K -band flux densities are systematically underestimated with respect to *WMAP*.

Since variability plays a large role here, the only secure way to address this is through simultaneous ATCA–VLA observations of the same set of sources, including a range in flux densities. Work is underway to resolve this issue. For the purposes of this paper, we will use our K -band flux densities as measured. However, we keep in mind the possibility that these are underestimated. Therefore, for example, when we discuss spectral indices involving the K band, we add/subtract 0.09 or $\log(1.23)$, where 1.23 is the median AT/VLA ratio, in order to test the effect of this discrepancy on our conclusions.

5.3. Strongly Variable Sources

The comparison of the VLA K -band observations from 2008 and 2009 revealed two sources that vary by $>50\%$. These are: J042315–012033 and J080512–011114. The comparison between the AT20G and VLA K -band fluxes revealed three sources where the AT20G/VLA ratio is >2 (after accounting for the $\sim 20\%$ systematic offset discussed above). These are: J080512–011114, J220643–003103, and J235013–020614. The first of these (J08512–011114) overlaps with one of the strongly variable sources revealed in the K -band data alone. For J042315–012033, the AT20G K -band flux density is in between the two values of our data. We address in more detail the spectral and polarization properties of these four sources in Section 6.5.

6. RESULTS

6.1. Morphology

A total of 26 of our sources show extended morphologies at one or more frequencies (16% of the sample). Figure 1 shows the images of all extended sources, where the gray scale shows

the higher resolution image and the contours show the lower resolution image, as indicated in the figure caption. Of these extended sources, only ~ 12 appear to be classic double-lobe radio galaxies: one shows a single strong jet, and one is a one-sided double-lobed galaxy; the rest are extended but without clearly defined jets, i.e., “blob”-like. Overall, roughly 2/3 of these resolved sources show clear cores. Combined with the low incidence of extended sources, this suggests that on the whole our sources are heavily core-dominated. In Figure 1, we can also see that the sources tend to get more extended with decreasing frequency (the contours are typically C or X band, while the gray scale shows the X or K band). We also note that for J094123–014251, the nominal AT20G position, on which we centered the VLA beam, actually corresponds to the northern lobe of a complex source. Our K -band image suggests a classic radio galaxy with two roughly symmetric prominent lobes and a faint core in between. In Table 3, we present the flux densities for both cores (when such can be distinguished) and for the total sources as measured using the AIPS routine IMSTAT with a rectangular aperture enclosing all visible extended emission.

Anecdotal evidence would suggest that 16% of the sample showing extended structures is significantly smaller than what one normally expects for lower frequency radio surveys. To test this assumption, we looked at the 1.4 GHz image of the *Spitzer* First Look Survey (FLS) field by Condon et al. (2003). We chose these data because they were obtained in the B configuration of the VLA resulting in a 5" FWHM beam, which is comparable to our observations, unlike the much worse resolution of all-sky surveys. Next, we look at the 16 sources in the FLS sample that have $S_{1.4\text{ GHz}} > 20$ mJy to be roughly comparable with our sources. We examined the image of each of these sources for extended or multi-component morphology, but ignoring fainter extended structures. We find that 9/16 (or 56%) show extended/complex morphology. This of course is not directly comparable to our results due to the differences in sensitivity and resolution. However, it does confirm that 20 GHz-selected sources are typically more compact than 1.4 GHz-selected sources, as expected.

Lastly, we briefly address polarization in extended sources. The core is typically the dominant source of polarized emission in the extended sources; hence the polarization percentages given in Table 3 are either those of unresolved sources or the cores in the case of extended sources. However, in one case, we find that the jets and lobes show rather spectacularly in polarized emission (see Figure 3). A more detailed analysis of this extended polarized emission, however, is beyond the scope of this paper. These highly polarized lobes in general have steep spectral indices and hence make negligible contributions at the frequencies used in most CMB and SZ experiments.

6.2. Spectral Indices and Color–Color Diagnostics

We determine spectral indices (using the convention $S_\nu \propto \nu^\alpha$) in various frequency intervals. In Figure 4, we plot two “color–color” diagnostic diagrams.¹² Such plots allow us to distinguish different classes of sources based on the shape of their SEDs, including in particular the gigahertz peak spectrum (GPS) sources (for a review, see O’Dea 1998). Our α_{CX} versus α_{XK} plot (Figure 4, top) looks very similar to the equivalent plot in Murphy et al. (2010), when we consider our much smaller

¹² We compute the spectral indices based on pairs of observations as close in time as available (for example α_{KX} is based entirely on 2008 K -band data, whereas α_{KQ} uses the 2009 November K -band data for the sources whose Q -band observations are from 2009 November).

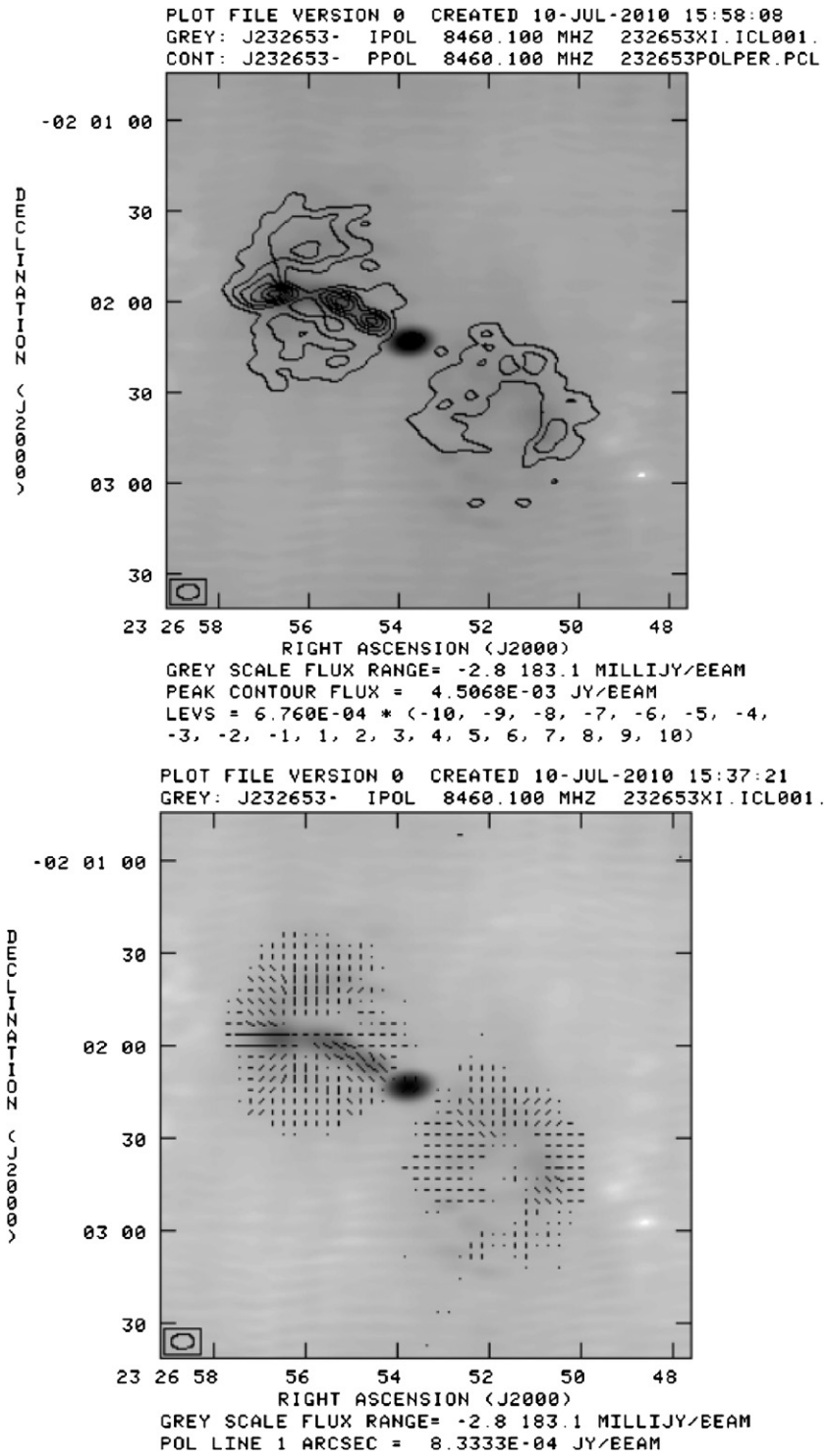


Figure 3. X-band polarization percentage map of J232653–020213, showing a prominent highly polarized (up to ~15%) jet that also has a kink in it. The top panel shows the total linear polarization overlaid on the Stokes *I* image in gray scale. The bottom panel shows the polarization angle map. Note that the core in this source is very weakly polarized. In both panels, the X-band beam is shown in the bottom left of the image.

sample (~160 versus ~6000). Comparing the distribution of spectral properties in our sources with the whole AT20G survey we find: 62% of our sources have steep or flat spectra,¹³ with both spectral indices <0 (versus 57% in AT20G); 22.5% fall in the lower right-hand (peaked-spectrum sources) quadrant (versus 21% in AT20G); 11% have inverted spectra as compared

to 14% in AT20G; and 4% (versus 8%) show a spectral upturn above ~8 GHz. The slightly smaller numbers of upturned and inverted spectrum and higher numbers of steep/flat and peaked spectrum sources can be accounted for in part by our slightly higher *K*-band frequency (22.46 versus 19.9 GHz), and in part by the ~20% discrepancy between our flux densities and those tabulated in the AT20G catalog. Murphy et al. (2010) define 45 sources (1.2% of the AT20G sample with 5 and 8 GHz

¹³ Flat spectrum sources have both spectral indices in the range -0.5 to 0.0.

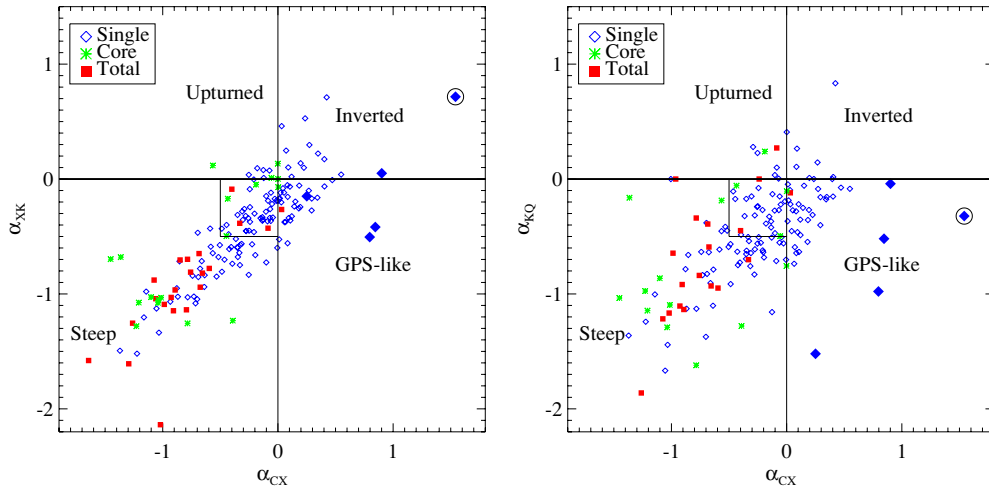


Figure 4. Radio color–color diagram for our sources based on the X – K spectral index (left) and the K – Q spectral index (right). The upper panel has artificially lower scatter due to the use of the X -band flux in both colors. We have labeled the locations of different classes of objects with the central square representing flat-spectrum objects as usually defined ($\alpha > -0.5$). The boundaries are largely historic and serve to facilitate classification, rather than having a rigorous physical meaning. Most interesting are the GPS-like or “peaked spectrum” sources, which represent 23%–27% of the sample depending on the colors used. The circled source is our only ultra-inverted spectrum source (following the definition in Murphy et al. 2010). (A color version of this figure is available in the online journal.)

data) as Ultra Inverted Spectrum (UIS) based on $\alpha_{XK} > 0.70$. Therefore, we should have 2 ± 1 UIS sources in our sample. We find one such object (J033427–015358) consistent with expectations.

The availability of the Q -band (43 GHz) data, however, allows us to go beyond what was done for the AT20G survey. Figure 4 (bottom) shows the α_{CX} versus α_{KQ} (our highest frequency spectral index) plot. We can immediately draw some conclusions: (1) our one UIS source now appears to be a peaked spectrum source, (2) the number of inverted spectrum sources is now lower (5%), and (3) the fraction of peaked spectrum sources is now slightly larger (rising from 23% to 26%).

Both panels show some correlation between the low-frequency spectral index and higher frequency spectral indices, especially for the steep spectrum sources. However, there is also considerable scatter, consistent with earlier AT20G results (Murphy et al. 2010). This scatter and changing distributions in spectral indices show why extrapolations of source counts from low-frequency surveys can produce misleading predictions of the numbers of sources at higher frequency, and hence of the contamination produced by such sources at the frequencies (>30 GHz) typically used in searches for CMB anisotropies. We return to this point in the discussion section.

Finally, as expected, we have a connection between morphology and spectral indices. In particular, the total flux densities of resolved sources generally have steep spectra. The same is true for most cores of resolved sources. In contrast, the single (i.e., unresolved) sources have somewhat flatter spectra and comprise almost exclusively the inverted spectrum and peaked spectrum sources.

6.3. Peaked Spectrum Sources

Figure 4 shows that a significant fraction of our sample have GPS-like (i.e., “peaked”) spectra. In total, we have 36 such sources, based on the α_{KQ} versus α_{CX} diagnostic plot (26%). If we account for the fact that our K -band fluxes may be $\sim 20\%$ too low, this would still leave us with 30 GPS-like sources (22.5%). This is comparable to expectations given the results in Sadler et al. (2006). Figure 4 however suggests that the bulk of these

are in the main “cloud” of sources, rather near the $\alpha = 0$ lines. Due both to flux density errors (for the sources near $\alpha \sim 0$) and variability, it is unclear whether some of the sources displaying GPS-like spectra are bona fide GPS (as discussed in Tornaiainen et al. 2007). Therefore, we generally use terms such as “GPS-like” or “peaked spectrum” throughout this paper.

However, there are a handful of sources that stand apart by being much more likely GPS sources. These are: J021121–014515, J033427–015358, J101956–002411, J211022–012658, and J230107–015804 (marked by the filled symbols in Figure 4). Of these, only J101956–002411 has a known redshift ($z = 1.13$); therefore, it is difficult to say where is the spectral peak in these sources in the rest-frame. However, they all have an observed spectral peak somewhere in the frequency interval 8–22 GHz, and are thus extreme examples of GPS sources, or high-frequency Peakers in the nomenclature of Dallacasa et al. (2000).

6.4. SEDs and Polarization Fractions

Figure 5 shows examples of the SEDs of our sources (separated into two classes—steep spectrum and inverted/GPS-spectrum sources), where we show both the total intensity SED and the polarized fraction of that SED. Figure 6 shows examples of the SEDs and polarization fractions of sources observed in two different epochs (2008 and 2009; see Section 3). These SEDs illustrate the spread in spectral classes in our sample as well as the typical variation of spectral index with frequency which complicates extrapolations from lower frequency data to the higher frequency regime (as in modeling the radio source population for CMB or Sunyaev–Zeldovich experiments).

Typically, we find low polarization fractions of only a few percent, although there are exceptions. When K - or Q -band polarized emission is detected, it tends to imply higher polarization fractions than seen in the C or X bands. This implied trend in rising polarization fraction with frequency may simply reflect the fact that the K and Q bands have lower sensitivities with regard to polarization percentages and hence only the more strongly polarized sources will have detections in those bands. In Section 6.6, we examine trends with the polarization fraction

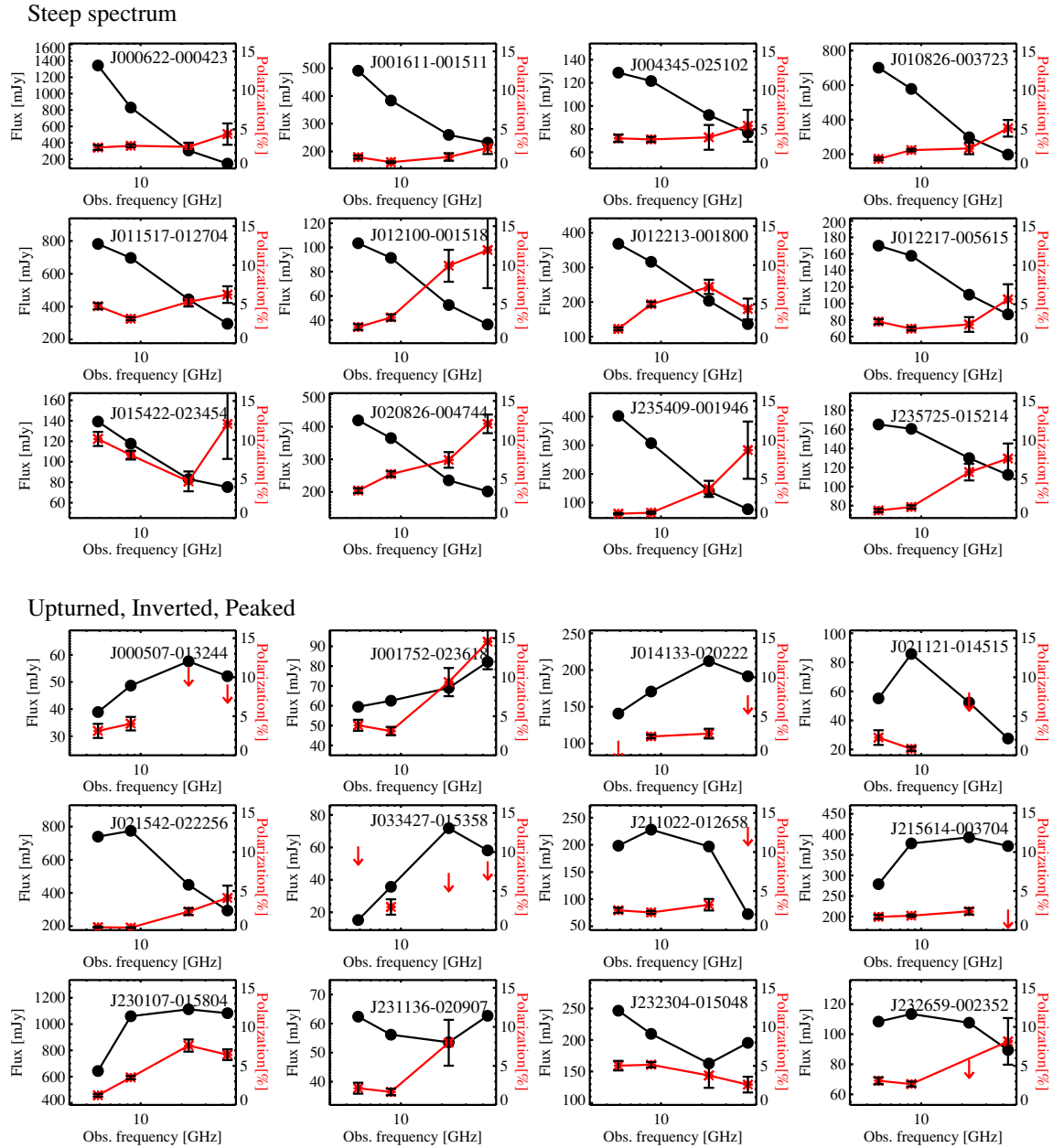


Figure 5. SEDs and polarized fractions for sources observed at a single epoch. The large filled dots and black lines indicate the flux densities. The red lines and error bars are for the polarization fractions. Dashed lines mean significantly different epoch of observations, whereas solid lines connect the different frequencies for which data were obtained over a couple of weeks or less.

(A color version of this figure is available in the online journal.)

for the whole sample including trends with frequency, spectral class, or flux density levels.

6.5. The Properties of Strongly Variable Sources in Our Sample

In Section 5.3, we listed four sources with strongly variable (i.e., >50%) *K*-band flux densities based either on our own two epochs of *K*-band observations or on the comparison between our *K*-band measurements and the AT20G values. These are J042315–012033, J080512–011114, J220643–003103, and J235013–020614. None of these sources are resolved in any of the frequency bands we study here. All except J080512–011114 are peaked spectrum sources. The first two sources show overall low polarization (typically a few percent) with the second two showing high-frequency polarization (though for

J220643–003103 the significance is questionable due to the large errors). For J042315–012033 and J080512–011114 although there is significant variability in the *K*-band Stokes *I* values from the two observing epochs, there is no detectable variability in the fraction of polarization which are in both cases low.

In Figure 7, we plot the available data for J042315–012033. This source flared dramatically between our 2008 and 2009 observations. The AT20G *K*-band flux is in between our two measurements. This source was also among the first we observed at the GBT in 2009 December and hence only a month after the November *K* and *Q*-band observations. Figure 7 shows a summary of the SED and its changes from 2008 to 2009 (see the caption of Figure 11 for the meaning of the lines and symbols). Other monitoring programs (A. Lähtenmäki 2010,

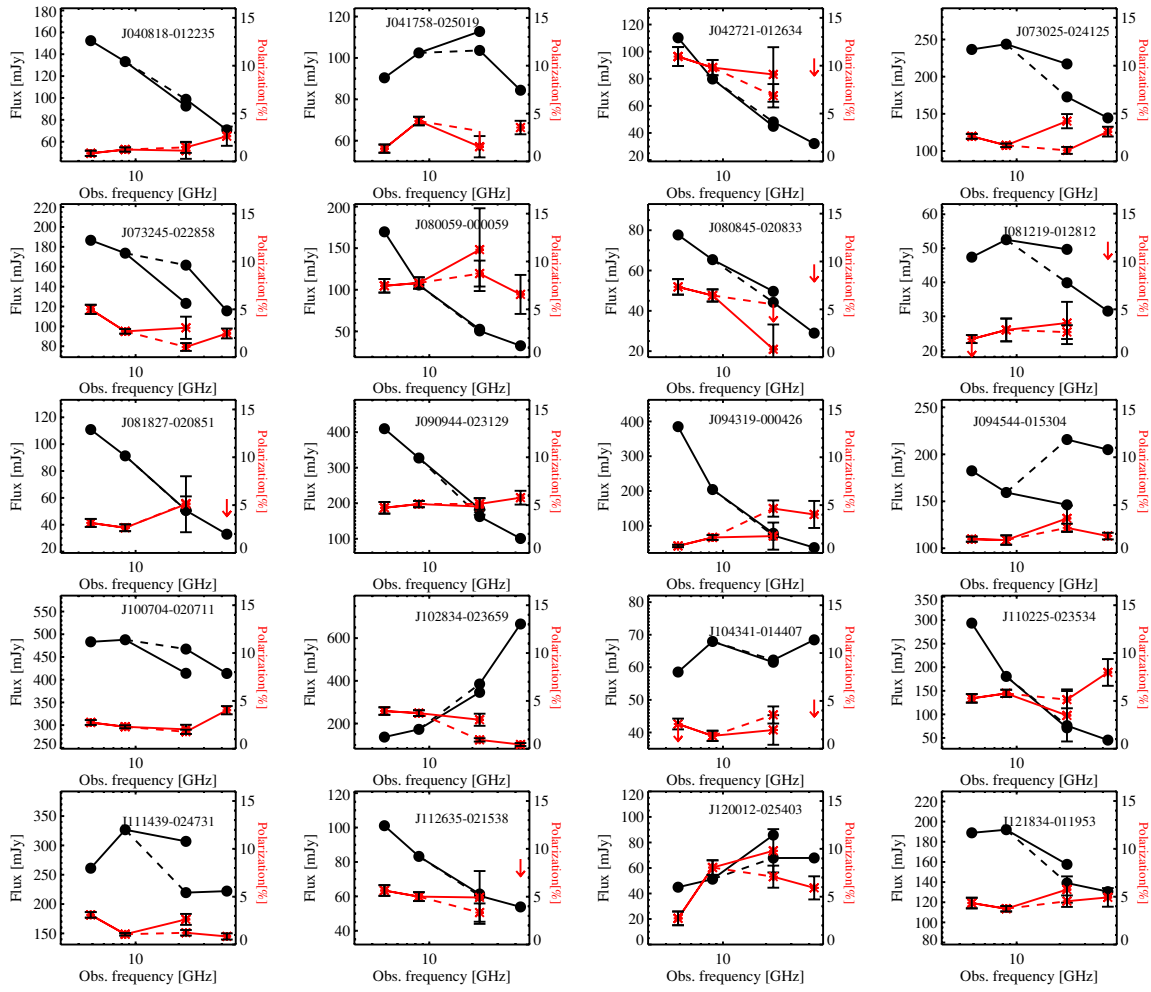


Figure 6. SEDs and polarized fractions for sources observed in two epochs (summer 2008 and 2009 November). The large filled dots and black lines indicate the flux densities. The red lines and error bars are for the polarization fractions. (A color version of this figure is available in the online journal.)

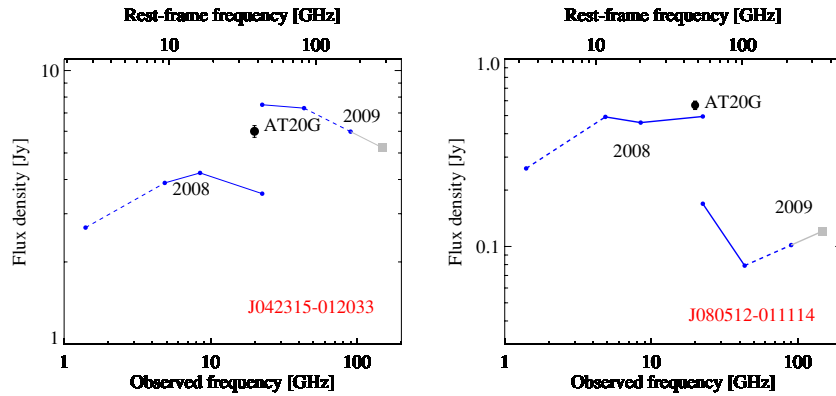


Figure 7. SEDs of highly variable sources. Left: the SED of J042315–012033. This is a known BLLAC and RL QSO with a redshift of $z = 0.914$. Right: the SED of J080512–011114 which has a redshift of $z = 1.388$. Note that as in Figure 6, solid lines indicate near-simultaneous observations, while dashed lines indicate non-simultaneous observations. In both cases, we also include the GBT 90 GHz data which were obtained about a month after the 2009 VLA data as well as archival NVSS 1.4 GHz flux densities. Finally, we also show the extrapolation to the ACT 148 GHz frequency (see Section 6.7 for more details). (A color version of this figure is available in the online journal.)

private communication) confirm the strong variability of this source during our observations. The polarized flux density seems to have increased roughly consistently with the total intensity flare, as the polarized fractions in the *K* band are comparable in the two epochs. This is a well-studied flaring source, whose 2009 flare is not even at the maximum observed in the past.

Hovatta et al. (2008) report results of long-term monitoring of this and other blazar sources and find a maximum of $S_{37 \text{ GHz}} = 15.7 \text{ Jy}$ for this source.

In Figure 7, we also show the available data for J080512–011114 which by contrast faded between 2008 and 2009. The AT20G data, from 2007, are consistent with our 2008

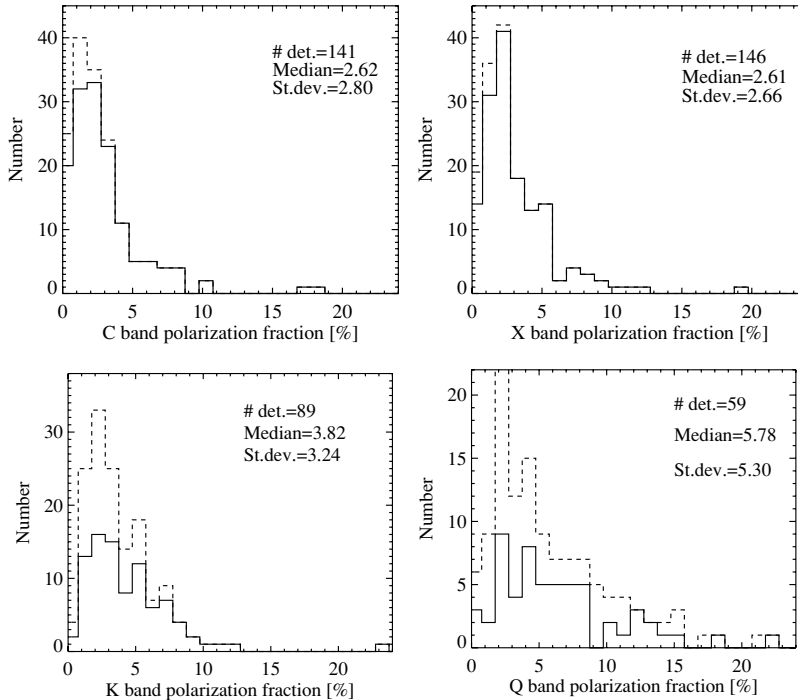


Figure 8. Polarization fraction histograms for the different bands. The solid histograms are for sources with detected polarization, while the dashed histograms include all polarizations as measured regardless of whether or not they are formally detected. Note the 95% upper limits for these cases are significantly larger and would push the histograms to the right (especially for the *K* and *Q* bands).

observations. Both of the sources highlighted in Figure 7 show the hazards of spectral classification in the presence of significant variability.

6.6. Polarization Fraction Trends

While our sample is smaller than that found in some other work on the polarization of microwave sources such as Tucci et al. (2004), Murphy et al. (2010), and Battye et al. (2011), it has some advantages.

1. We used a high-frequency-selected sample, drawn from the AT20G survey (see Sadler et al. 2006; Murphy et al. 2010 for a discussion). We are thus selecting an extreme population, dominated by cores or unresolved sources. These sources, with their typically flat spectra, are those most likely to have high enough high-frequency flux to interfere with SZ and CMB measurements, typically made in the 30–150 GHz region. High-frequency-selected sources are also likely to be less affected by Faraday depolarization.
2. Our sensitivity in both polarization and total power is significantly higher than the much larger AT20G survey, so we could push to lower values of polarization percentage, p . Because our sample is unbiased with respect to its parent sample (the AT20G survey), as shown for instance by the very similar distribution in spectral properties, our conclusions here are likely to apply for the whole AT20G sample.
3. Because of our nearly simultaneous observations, at least in sets of *C+X* and *K+Q* bands, any trends in the polarization fraction with frequency we find would have a higher significance than a collection of observations at different epochs.

We have computed the linear polarization fractions or upper limits for each band following the prescription in Section 3.4 (see Table 3). For extended sources, we compute only the

polarization of the core. Some of the missing values in Table 3 correspond to extended sources where the core is not clearly distinguishable in a given band (others are genuinely missing data, such as the calibrator 0725–009 which was observed only in the *K* and *Q* bands). Finally, for some of the weakest *Q*-band sources, which we could not self-calibrate, we could not obtain useful values of S_Q or S_U .

Figure 8 shows the polarization fraction histograms for each of the bands (*C*, *X*, *K*, and *Q*). Here, we include all the p_{corr} values estimated following Equation (4). A number of these sources, especially in the *Q* band, are not actually detected in the polarized flux (using the upper limits for those would shift these histograms to the right). The polarization fractions we find are typically a few percent, although a tail of more strongly polarized (up to $\sim 10\%$) sources exists in all frequencies. The most striking aspect of Figure 8, however, is that the polarization fraction seems to increase with frequency.

Figure 9 shows the median polarization fractions of our sources separated by spectral type and flux density. The trend of increasing polarization with increasing frequency (at least for the sources with detected polarizations in the *K* and *Q* bands) is quite evident. In this figure, the dotted line shows the trend for all sources that have polarization detections in all four bands. This suggests that at least for these ~ 60 sources, this trend is real. However, where data are available, we have 62 sources with measured *Q*-band polarization and 65 with upper limits on p_Q . Would the observed trends hold if we had detections in these 65 sources as well? We looked at the spectral classes of these 65 *Q* band upper limits and find only nine “steep” spectrum sources (defined as $\alpha < -0.5$), versus 18 “gps” sources. This suggests that, even if all these sources have very low *Q*-band polarizations, the trend seen in Figure 9 (top) for steep spectrum sources will be maintained. Looking at their fluxes virtually all of these 65 sources have $S_K < 200$ mJy (their median flux density is 67 mJy). This is certainly not surprising as polarization

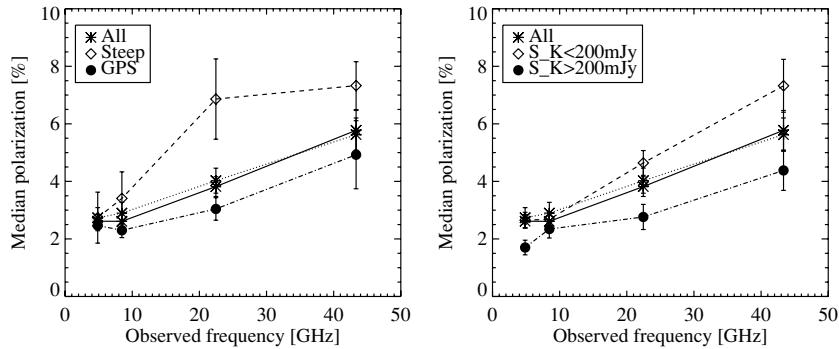


Figure 9. Median polarization fractions for the different bands as a function of spectral type (left) and flux density (right). The dotted line represents the median polarizations per frequency for sources with detected polarizations in all four bands.

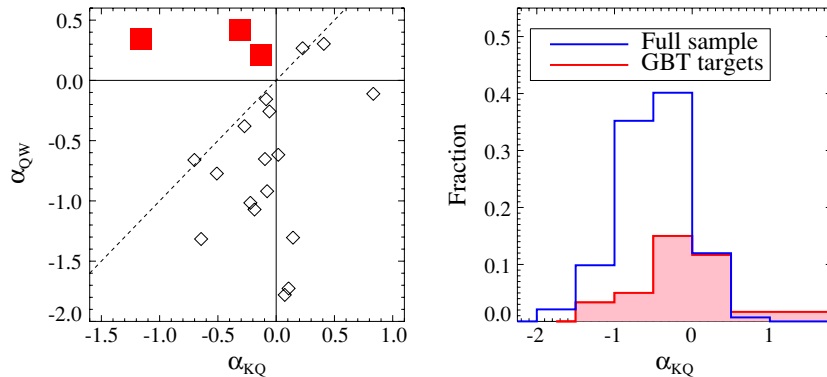


Figure 10. Left: the spectral index diagnostics from the K band (22 GHz) to the W -band (90 GHz). The dashed line shows the $y = x$ line where extrapolations from the K and Q bands predict perfectly the 90 GHz fluxes. Due to the likelihood of resolved out flux, we omit extended sources from this plot. Right: the K – Q spectral index for the whole sample compared with the GBT targets. The GBT sub-sample is biased toward flatter spectrum sources.

(A color version of this figure is available in the online journal.)

is harder to detect in fainter sources; however, it does suggest that the trend in Figure 9 (bottom) is less robust to the effects of these upper limits.

6.7. Extension to 90 GHz

Table 4 shows the measured 90 GHz fluxes compared with extrapolations based on our α_{KQ} spectral indices. The last column shows the ratio of measured-to-expected flux densities. Some of the deviations from unity may be due to variability. However, a much stronger factor likely changes in the spectral index in the ~ 20 –90 GHz range (see Table 5). In particular, it is noticeable that for the bulk of the sample the measured flux densities are below the extrapolated ones. Figure 10 shows a color–color diagnostic diagram extending to 90 GHz. Note that 19/24 of the sources are below the $y = x$ line, suggesting simple extrapolation from 43 GHz will overestimate the true 90 GHz flux densities. The three outliers which actually show a significant upturn from 43 to 90 GHz are intriguing. This may partially be due to variability as the 90 GHz observations were not simultaneous with the K - and Q -band observations. Figure 11 shows a few examples of the SEDs of compact/point-like sources with 90 GHz data. Most of these were observed at the GBT in 2009 December and the last three were in our 2009 November $K+Q$ sample. Therefore, the 22–90 GHz observations were all done within about a month of each other. One of these sources, J080512–011114, is one of the sources that shows an upturn between 43 and 90 GHz. However, as discussed in Section 6.5, this source is also among the most strongly variable sources in our sample. Potentially variability could explain the other two outliers here.

The extrapolated values shown in Table 4, of course, depend on the α_{KQ} values which in turn depend on the K -band flux densities. However, in Section 5.2, we showed that our K -band flux densities may be underestimated compared with the AT20G survey flux densities. We test the effect of this by multiplying our K -band values by the median offset from the AT20G values, 1.22, and re-extrapolate to 90 GHz. Table 4 shows the resulting values. The ratios of these modified extrapolated values to the observed 90 GHz data are clearly closer to unity than the ratios before the above modification.

Sadler et al. (2008) followed up 70 AT20G sources at 95 GHz (with no overlap with our GBT sample). They found a median α_{KW} value of -0.39 . For our smaller sample, we find a median of -0.32 and a standard deviation of 0.40. Without adjusting for the difference in central frequencies (for either the K or W band), the two median values are in reasonably good agreement. The spread in our α_{KW} is comparable to that in Sadler et al. (2008) as seen in their Figure 5. Although of marginal significance, the slightly steeper slope found by Sadler et al. (2008) might be an indication of further downturn in the spectra (as their W band is of higher central frequency than ours), or again might reflect the difference between our VLA K -band flux densities and the AT20G ones.

7. DISCUSSION

7.1. The Degree of Polarization of 20 GHz-selected Sources

Figure 9 shows the median polarization fractions in our four observed bands as a function of spectral type and flux density. These values exclude upper limits. Nevertheless, it is

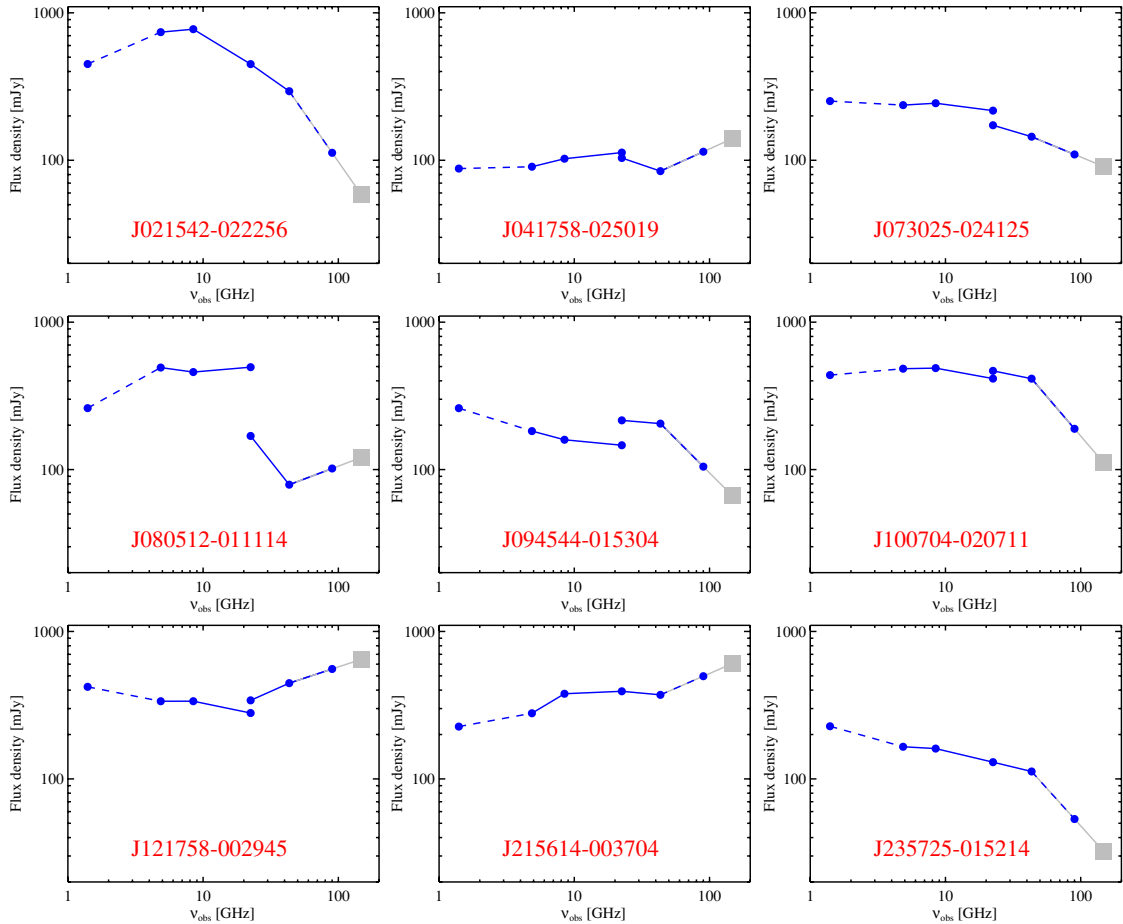


Figure 11. SEDs of some of our sources where we also have 90 GHz observations that were taken within about a month of the VLA observations. The blue lines show the SEDs based on the data reported here (we also include earlier NVSS 1.4 GHz flux densities based on NED data). Dashed lines indicate non-simultaneous observations. The thin gray lines are constant slope extrapolations of our data to the ACT frequency of 148 GHz (large gray square).

(A color version of this figure is available in the online journal.)

clear that the median polarization fraction rises with frequency. This trend is reminiscent of earlier results such as the multi-frequency polarization estimates of a 400 MHz-selected sample presented in Klein et al. (2003) and a small sample of 15 active galactic nuclei whose 43–300 GHz polarization fractions were studied by Jorstad et al. (2007). Similar to Klein et al. (2003), we find that this effect is stronger for the steeper spectrum sources, while the polarization fraction is nearly constant with frequency for the peaked-spectrum sources. However, Klein et al. (2003) find a median polarization of $\sim 4.5\%$ at 15 GHz for their low-frequency-selected sample (and nearly 6% for their steep spectrum sources). These values are higher than our data interpolated to 15 GHz. It is important to recognize, however, that we report polarization figures only for unresolved sources or the cores of resolved sources, thus ignoring the potentially more polarized lobes found in many radio galaxies (see for instance Figure 3). Nevertheless, this comparison suggests that the degree of polarization of our 20 GHz-selected sample is somewhat lower than that of low-frequency-selected samples. The general trend of decreasing polarization with increasing wavelength is also expected from Faraday depolarization (Burn 1966).

Battye et al. (2011) analyze the 8–43 GHz polarization properties of *WMAP* sources, in particular as a means to determine the level of point source contamination in CMB polarization measurements. They find polarization fractions

of typically $\sim 2\%$ and little change with frequency. This is at first glance contradictory to our finding. However, *WMAP* point sources have significantly higher flux densities and tend to have even flatter spectra than our sample. The increase in the polarization fraction with frequency is most significant in steep spectrum sources as observed by Klein et al. (2003) and confirmed for our high-frequency-selected sources here (Figure 9). In addition, the spectra of our sources flatten (as estimated by α_{KQ}) as the *Q*-band flux density increases (Figure 10). The apparent contradiction between our results and Battye et al. (2011) can be easily resolved by some combination of these two effects.

7.2. High-frequency GPS

Our sample includes 36 peaked or GPS-like sources, many of which are by selection high-frequency peakers (at ~ 10 – 20 GHz in observed frequencies). This high turnover frequency can be the result of younger ages (Dallacasa et al. 2000) or lower redshifts than low-frequency-selected GPS. We used NED¹⁴ to determine likely optical associations and redshifts for our sources. We found that 7/12 of our GPS-like sources with available redshifts have $z > 1$ (the median value is 1.2 ± 0.6 with the lowest redshift being 0.112 and the highest 2.160). These moderate redshifts suggest that an intrinsic

¹⁴ The NASA Extragalactic Database.

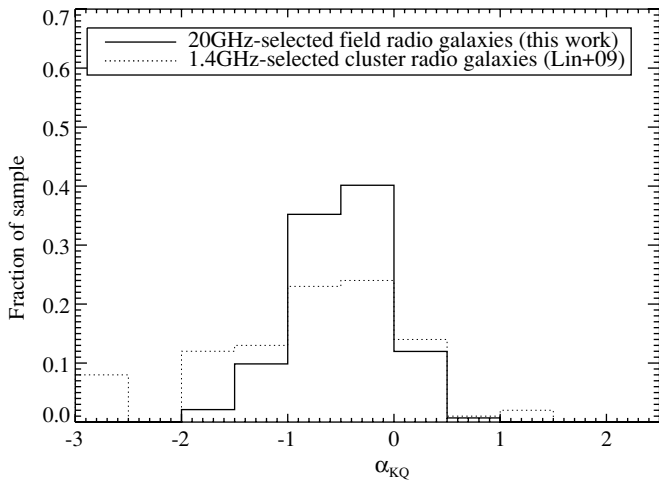


Figure 12. Spectral index distribution for our sources compared with the known cluster radio galaxies in Lin et al. (2009).

spectral difference (perhaps resulting from their youth) is more likely an explanation. In addition to the Stokes I flux densities, we also report here the polarized fractions for our four observational bands. All of our GPS sources have measurable polarizations of typically $\sim 1\%$ – 2% but in some cases higher (e.g., J121834–011953 has polarization fractions of $\sim 4\%$ across all bands). By contrast, the earliest polarization studies of GPS sources (Rudnick & Jones 1982) conducted in the centimeter regime suggested very low polarization fractions of under a percent for these sources.

7.3. Comparison with Cluster Radio Galaxies

One of the principal motivations for this work was to better understand the radio galaxy contamination in SZ surveys. Such an analysis was performed by Lin et al. (2009) for the case of 1.4 GHz-selected, low-redshift radio galaxies that are known cluster members. That work concludes that a significant fraction of these sources have an upturn between 22 GHz and 43 GHz ($\alpha_{KQ} > -0.5$) contrary to simple extrapolation from 1.4 GHz as has been done in the past. In Figure 12, we compare the α_{KQ} distribution for our sample (including unresolved sources plus total fluxes for resolved sources) with the sample distribution for the Lin et al. sample. We find that the range covered by the two samples is very similar, with the exception that we are missing the most extreme steep spectrum sources. However, our distribution is more “peaked” than the 1.4 GHz-selected sample. In particular, in our sample, 56% of the sources have $\alpha_{KQ} > -0.5$, while only 41% of the 1.4 GHz-selected cluster radio galaxies meet the same criterion. Moreover, the significant fraction of GPS-like sources in our sample supports the well-known fact that single power-law extrapolation from 1.4 GHz based luminosity functions in modeling the radio point sources at higher frequencies is unlikely to be adequate. Note that the Lin et al. (2009) paper assumes the same VLA flux scale as used here and hence this direct comparison is valid even though there is a possibility of our K -band fluxes being underestimated (Section 5.2).

7.4. Implications for Millimeter-wave Cosmology Surveys

The differences we find in this work (usually reinforcing earlier results) regarding the nature of high-frequency-selected sources, as compared with low-frequency-selected sources, in terms of morphology, spectral index, and polarization fraction

all suggest that an accurate modeling of the radio galaxy contamination of millimeter-wave cosmological surveys requires starting with high-frequency-selected samples and simultaneous multi-frequency observations (to model the spectral index and control for variability). In this fairly speculative section, we use the α_{KQ} spectral index to extrapolate our measured flux densities to 148 GHz to estimate the expected flux density distribution of these sources in the lowest frequency band employed by ACT. The resulting extrapolated fluxes for our sources tend to cluster in the 10–100 mJy range, and hence are observable by ACT. However, in Section 6.7, we found that measured 90 GHz flux densities were somewhat below extrapolations based on the α_{KQ} indices. Some of this can be attributed to variability; however, the one-sidedness of the effect suggests that the spectra do indeed steepen from ~ 40 GHz to ~ 90 GHz. This by necessity would also affect the extrapolated 148 GHz fluxes. Because of the effects of variability (in general the 90 GHz data were not simultaneous with the 43 GHz data) and the fact that GBT observations were only performed for the brightest sources in the Q band, we cannot safely generalize these conclusions to the whole sample.

We next ask what is the contribution of radio galaxies (as selected by the AT20G survey) to the ACT survey. This can be done by extrapolating the AT20G number counts to 148 GHz. A significant excess between the measured ACT number counts and this extrapolation should reveal either: (1) a population not present in the AT20G survey, or (2) an upturn in the AT20G sources’ spectra as might be expected from, for example, free-free or even dust emission. A significant deficit might reveal that the AT20G spectra actually steepen as our GBT results, for example, suggest. Of course, these effects (if present) might cancel each other on average and not leave a significant imprint on the number count. Therefore, once the equatorial ACT data become available, we plan to perform a source by source comparison between our results and the measured 148 GHz fluxes for this particular sample.

Figure 13 (top left) shows the AT20G integral number counts, where for comparison we also overlay the model from de Zotti et al. (2005). Note the survey limit of ~ 40 mJy at 20 GHz. In order to extrapolate to 148 GHz, we assume that our α_{KQ} distribution (Figure 12) is applicable for the whole AT20G sample (a good assumption) and that it is independent of flux density (likely a poor assumption given the discussion above). Figure 13 (bottom left) shows the resulting extrapolated number counts at 148 GHz compared with the SPT results as given by Vieira et al. (2010), and preliminary ACT results as given by Marriage et al. (2010). We find that while we come reassuringly close to the observed number counts for the higher flux densities ($S_{148} > 60$ mJy), we come under the observed counts at lower flux densities. Our 20 GHz limit of ~ 40 mJy, combined, with an on average negative α_{KQ} (median = -0.46), suggests that incompleteness cannot fully explain this shortfall (that should come at flux densities < 40 mJy). We can conclude from this rough analysis that the higher flux density SPT sources are fully accounted for by the radio population as seen by the AT20G, while an additional population or emission component to the radio galaxies might be present in the SPT counts at a few 10 s of mJy. The right-hand side of Figure 13 shows the same but for the 20 GHz and extrapolated 148 GHz differential number counts. Here again we find that the faint end of our extrapolated counts at 148 GHz is slightly lower than the observed SPT counts. If our K -band flux densities are underestimated by $\sim 20\%$, then it would depress the extrapolated 148 GHz counts.

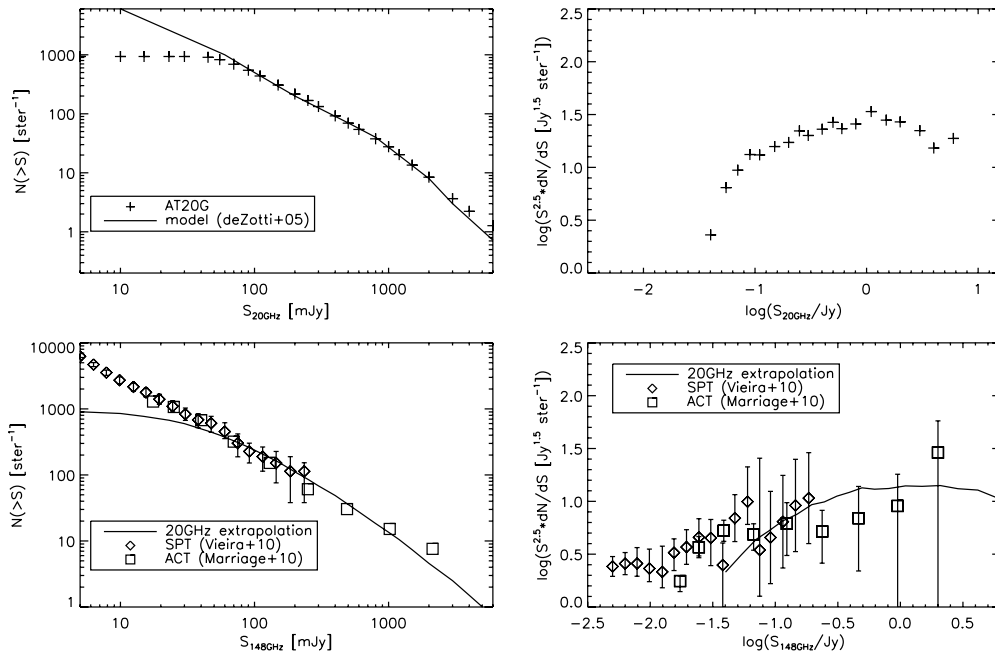


Figure 13. Top panels are the AT20G number counts where integral counts are shown on the left and normalized differential counts on the right. The extrapolated 148 GHz counts are shown on the bottom (solid line) where for comparison we also overlay the SPT (Vieira et al. 2010) and ACT number counts (Marriage et al. 2010).

The preliminary ACT number counts (Marriage et al. 2010) are indeed systematically lower than our extrapolation. While a potential underestimate of our KQ spectral indices (and hence overestimate of the KQ spectral index) might account for some of the discrepancies, a more likely explanation is the steepening of the SEDs of radio sources. Our finding of a median $\alpha_{KQ} = -0.14$ and a median $\alpha_{QW} = -0.47$ (see Table 5) supports this view.

8. SUMMARY AND CONCLUSIONS

1. In our sample, only 26 out of 159 sources (16%) are extended. This is not surprising, given the steep spectra of radio lobes and the growing dominance of core emission as we move to higher frequencies. This fraction of extended sources is only about half of that found by Bolton et al. (2004) using 1.4 GHz morphologies.
2. Using K -band observations at two epochs, we explore the level of variability in our sources. We find a median variability of $\sim 6\%$. We highlight J042315–012033, which flared dramatically in 2009.
3. On average, the spectral indices tend to steepen between 20 and 90 GHz—such that some inverted spectrum sources in the AT20G survey appear “peaked spectrum” sources when the 43 GHz VLA data are included. The trend continues with the 90 GHz data, where available, although a small subset of these sources shows an upturn from 43 to 90 GHz. These data will be very useful to modeling efforts to understand the general radio source population contamination to SZ surveys.
4. The observed polarization fractions are typically $\sim 2\%$ – 5% , with a tail extending up to $\sim 15\%$. We observe an increase of the median polarization fraction with frequency. This effect is strongest for the steep spectrum sources. Flatter spectrum and higher flux density sources tend to have lower high-frequency median polarization fractions. This is broadly consistent with recent results on *WMAP* sources

(Battye et al. 2011) and suggests that radio point sources polarization is unlikely to be a dominant foreground for CMB polarization measurements.

5. As expected, our 20 GHz-selected galaxies show a higher fraction of flat and inverted spectrum sources than seen in recent studies of 1.4 GHz cluster radio galaxies. Our observed distribution of α_{KQ} in conjunction with the AT20G number counts provides a better constraint on the number of discrete radio galaxies that can be expected in current and upcoming SZ surveys.
6. In this work, we discover an inconsistency between the VLA and ATCA 20 GHz absolute flux scale, in the sense that the VLA fluxes tend to be $\sim 20\%$ lower. Such a discrepancy was first presented in Murphy et al. (2010), but at a lower level, although we argue that this is mostly due to the higher flux densities probed in that work. While we discuss various possibilities here, the cause of this offset is as yet unknown. Planned, simultaneous, ATCA and VLA observations should be able to resolve the issue. Throughout this paper, we address the effect of this discrepancy where appropriate.

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