CONTRIBUTION OF BRIGHT EXTRAGALACTIC RADIO SOURCES TO MICROWAVE ANISOTROPY

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ABSTRACT

We estimate the contribution of extragalactic radio sources to fluctuations in sky temperature over the range of frequencies (10–300 GHz) used for cosmic microwave background (CMB) anisotropy measurements. CMB anisotropy observations at high resolution and low frequencies are especially sensitive to this foreground. Our catalog of 2207 bright radio sources includes 758 sources with flux measurements at 90 GHz. We develop a method to extrapolate the source spectra and predict skymaps of extragalactic radio sources at instrument resolutions of 10″–10′ FWHM. Our results indicate that the brightest radio sources will dominate microwave anisotropy for a wide range of resolutions and frequencies. We predict the location and flux of the brightest radio sources at each frequency, making it straightforward to develop a template for masking the pixels containing them. This masking should be sufficient to protect most CMB anisotropy observations from unacceptable radio source confusion.

Subject headings: catalogs — cosmic microwave background — radio continuum: galaxies

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1. INTRODUCTION

The Cosmic Microwave Background Explorer (COBE) detection of large angle CMB anisotropy (Smoot et al. 1992) has sparked a drive to measure the anisotropy on smaller angular scales with the goal of determining crucial information about the density and expansion rate of the universe, the nature of dark matter, and the spectrum of primordial density perturbations. COBE DMR observations were basically unaffected by extragalactic foreground sources (Banday et al. 1996; Kogut et al. 1994) due to the large beam size (7″ FWHM). Because the contribution of a point source increases with the inverse of the beam area, observations at higher angular resolution are more sensitive to extragalactic foregrounds, including radio galaxies (Toffolatti et al. 1999), bright infrared galaxies (Gawiser & Smoot 1997), high-redshift infrared galaxies (Blain et al. 1998; Gawiser, Jaffe, & Silk 1998, hereafter GJS), and the Sunyaev-Zeldovich effect from galaxy clusters (Aghanim et al. 1997; Refregier, Spergel, & Herbig 1998). Estimates of extragalactic foreground confusion are critical as many ground-based, balloon-borne, and satellite experiments (MAP, Planck Surveyor) plan to study CMB anisotropies at angular scales from 5′ to 30′, and significant results are already available (e.g., Jaffe et al. 2000; Netterfield et al. 1997; Scott et al. 1996).

To evaluate the impact of known radio sources on CMB anisotropy observations, we use data from a variety of catalogs (see § 2) to construct models of source spectra as a function of frequency. We leave the possible impact of additional undiscovered populations of sources to other analyses (see GJS for a discussion). We analyze simulated skymaps at frequencies from 10 to 300 GHz to determine the expected contribution of radio galaxies to foreground confusion of CMB temperature anisotropy. This information will be useful when choosing frequencies and regions of the sky for CMB anisotropy observations. This work represents a significant improvement over previous efforts (Toffolatti et al. 1999, 1998, 1995; Franceschini et al. 1989) which depended upon galactic evolution models to predict the contribution of simulated radio sources at microwave frequencies. Our catalog contains detailed observations of known sources and hence can be used to make a spatial template for masking out their emission, and this phenomenological approach should lead to greater accuracy in predicting source counts and the overall level of foreground anisotropy.

2. RADIO SOURCE CATALOG

The radio observations used in this project were compiled from a number of separate catalogs. Our current catalog includes flux measurements and their corresponding errors at multiple frequencies for 2207 sources. We have focused our attention on obtaining all available radio observations at millimeter and submillimeter wavelengths, resulting in 5766 observations of 758 different sources at 90 GHz, 890 observations of 229 different sources from 100–200 GHz, and 2628 observations of 309 different sources at frequencies above 200 GHz. The sources are roughly isotropic in distribution, except for a significantly greater number of sources in the northern celestial hemisphere due to the anisotropic distribution of radio telescopes on Earth. In addition, there are noticeably fewer observations within 10° of the galactic plane and the celestial north pole due to the difficulty of observing extragalactic radio sources in those locations.

Our catalog includes the full-sky 5 GHz–selected 1 Jy sample of Kühr et al. (1981). We have added high-frequency (> 90 GHz) measurements (Steppe et al. 1988, 1992, 1995; Tornikoski et al. 1996; E. Krysa 1998, private communication; Antonucci, Barvainis, & Alloin 1990; Beichman et al. 1981; Chini et al. 1989; Gear et al. 1994; Edelson 1987;
The spectra of many extragalactic radio sources are approximated well over a wide frequency range by a simple power law with spectral index $\alpha$,

$$S \propto \nu^{-\alpha}.$$ (1)

The vast array of radio sources can, however, lead to a large dispersion in the spectral index across various frequency ranges (see Begelman, Blandford & Rees 1984, Verschuur & Kellerman 1988, and Condon 1992 for a review). The complex spectra of these objects arise primarily from the effects of synchrotron self-absorption in compact regions, which leads to spectral indices in the range $\alpha = -2.5$ to $\alpha \approx 0.5$. At frequencies above the self-absorbed region the spectra are optically thin, with $\alpha = 0.5$ to $1.0$, and at yet higher frequencies synchrotron losses steepen the spectra.

To determine if there are discrete spectral types, we use sources that have been measured near 1.4, 10, and 90 GHz and plot each source’s spectral index from 1.4 to 10 GHz versus its index from 10 to 90 GHz in Figure 1. There is a vague clustering of bright sources (circles) consistent with the notion that the brightest sources selected at low frequencies tend to have steeply falling spectra. The overall scatter of source spectra in Figure 1 shows that it is wrong to categorize radio sources into template spectra or a narrow spectral index range. This motivates us to fit the spectra of each source individually. A previous phenomenological approach (Tegmark & Efstathiou 1996) extrapolated 1.4 GHz source counts by assuming flat-spectrum emission for all sources. Our method has the advantages of using the actual source locations, which can be turned into a template for masking the brightest pixels on the sky, and of choosing the spectrum for extrapolation on a case-by-case basis.

To determine the frequency beyond which a power law can be fitted to the spectrum of a given source, we use an iterative model which starts with the best-fit line to the three highest frequency data points (in log flux vs. log frequency) and repeatedly includes the next highest frequency data point to the set to which it fits a line. The fitting stops when the reduced $\chi^2$ starts to get worse or becomes acceptable ($\approx 1$). There is little evidence that inverted spectra are common past 30 GHz (Steppe et al. 1995; Stanghellini et al. 1997), so we set the few inverted ($\alpha \geq 0$) high-frequency spectra in the catalog to flat ($\alpha = 0$) spectra. Upon closer inspection, these inverted spectra appear to result from variable sources being observed at different epochs at different frequencies, and we find that most of the sources with $\alpha_2 < 0$ in Figure 1 based on their mean 10 and 90 GHz fluxes are better fitted by an $\alpha \geq 0$ power-law when all observations are taken into account. The average high-frequency spectral index was 0.5 with 27% of the sources in our catalog having steep spectra ($\alpha > 0.75$), and 37% having flat spectra ($\alpha < 0.25$).

There could also exist a population of sources with spectra rising up to 30 or even 90 GHz, analogous to the known gigahertz-peaked spectrum sources. While we do not see evidence for such sources in our catalog, they could be too dim to be part of the samples originally selected at 1.4 GHz but still contribute significantly at 90 GHz and higher frequencies. Falcke et al. (1999) have indeed seen evidence for this in the behavior of the spiral galaxy III Zw 2 which they observed in outburst with a spectrum peaking at 43 GHz. As sources of this type are variable as well as dim at 1.4 GHz, they will be quite difficult to predict and must be detected as 5 $\sigma$ sources in the observations of interest or by simultaneous monitoring at similar frequencies and much higher resolution. The likely impact on the Planck mission of a similar family of inverted-spectrum sources is discussed by Perna & Di Matteo (2000).2

To check the accuracy of our techniques, we ran our extrapolation method on sources with observations at 90, 150, and 230 GHz while ignoring the observations above certain frequencies and then compared the measured fluxes with the extrapolated fluxes. The results (Table 1) show that the extrapolation method works best when there is at least one measurement at 20 GHz or greater, as expected since many spectra become power law past 5 GHz. Table 1 shows that on average we overpredict the flux at 90 GHz by a factor of 1.6, even when measurements above 20 GHz are used. However, the median such error factor is only a factor of 1.1 overestimate, so we have roughly an equal number of over- and underestimates. This is no longer the case at 230 GHz, where even the median error factor is 1.9; our extrapolation method is overestimating the typical flux due to flat spectra falling off to more typical synchrotron spectra.

Fig. 1.—Spectral indices $\alpha_1$ from 1.4 to 10 GHz and $\alpha_2$ from 10 to 90 GHz. Solid circles represent the brightest sources at 1.4 GHz; open squares represent dimmer sources at 1.4 GHz. Note the lack of clustering into distinct archetypal spectra.

2 These authors only report predictions at 30 GHz, but their models would actually have a much more serious impact at 90 GHz. However, even the low-luminosity model proposed by these authors is ruled out by the limits of GJS.
at frequencies around 100 GHz (Gear et al. 1994). It is difficult to predict how far this fall-off will last, as thermal emission from low levels of dust in these radio-bright galaxies are expected to dominate their spectra by 500 GHz, except for the BL Lac objects which have flat spectra up to infrared wavelengths (Knapp & Patten 1991; Chini et al. 1989; Landau et al. 1986). We therefore only trust our extrapolation in the range that has been tested, up to a maximum frequency of 300 GHz. As the radio sources that have been observed at 30–300 GHz were selected at lower frequencies for brightness and flat spectra, our determination of uncertainties may not apply to dimmer or steeply falling radio sources. However, these bright, flat-spectrum sources are expected to dominate the radio contribution to CMB anisotropy observations. When interpolation is required, we use a cubic spline which passes through the mean fluxes at the observed frequencies. We visually inspected the modeled spectra of all 2207 sources to check the algorithm and eliminate any serious errors or outliers.

In Table 2 we use our spectral fitting technique to derive whole sky source count statistics showing the level of completeness of our catalogue. In particular, Table 2 lists the number of sources predicted and observed (the latter parenthesized) at different flux density levels for a number of frequencies.

For planned CMB anisotropy experiments, an additional concern is that the flat-spectrum radio sources can vary by up to a factor of 10 in flux since their emission comes from a compact, active core. Typical variations occur on timescales of 1 month to 1 year, although the overall spectrum shape is often preserved for a decade or longer (Tornikoski et al. 1993). We use the scatter in the observed fluxes of a source at each frequency to estimate the typical range of variability, which yields an error bar on the source's flux at that frequency about the mean of all observations. Because the variations are not periodic, there is little more that can be done, unless sources are observed nearly simultaneously at higher resolution and nearby frequencies.

Radio sources are typically 4%-7% polarized, and this polarization is variable (Nartallo et al. 1997), so radio-source foreground subtraction will be an important consideration for CMB polarization observations as well. Since the polarization of most individual sources has not been measured and is variable, masking of radio sources will be particularly necessary for low-frequency CMB polarization observations.

4. RESULTS

We use the fitted spectra to predict the microwave flux of each radio galaxy in Jy (1 Jy = 10^{-26} W m^{-2} Hz^{-1}). To convert from flux $S$ to antenna temperature $T_A$, we use

$$T_A = S \frac{\lambda^2}{2k\Omega},$$

where $k$ is Boltzmann's constant, $\lambda$ is the wavelength, and $\Omega$ is the effective beam size of the observing instrument. The antenna temperature of the cosmic microwave background radiation, which has a thermodynamic temperature of $T = 2.73$ K, is given at frequency $\nu$ by

$$T_A = \frac{x}{e^x - 1} T,$$

defining $x \equiv h\nu/kT$. Fluctuations in antenna temperature caused by point sources will appear as thermodynamic temperature fluctuations in the CMB according to

$$\frac{dT}{dT_A} = \frac{(e^x - 1)^2}{x^2e^x}.$$

The intrinsic $\Delta T/T$ of the CMB found by COBE is $\approx 10^{-5}$ and is expected to vary between that and $3 \times 10^{-5}$ at the angular resolutions considered here (Gawiser & Silk 2000). An analysis of source counts indicates that the northern celestial hemisphere subset of our catalog becomes incomplete at an extrapolated flux of 1.0 Jy at 90 GHz, while the southern hemisphere is incomplete below 2.0 Jy at 90 GHz. For the purposes of statistical analysis we have concentrated on the northern hemisphere where we appear to have

### Table 1

#### Average Errors from Extrapolation

| Frequency | Frequencies Ignored (GHz) | Average Error | Average Error Factor |
|-----------|---------------------------|---------------|---------------------|
| 90        | $\geq 2$                  | 2.1           | 2.5                 |
| 90        | $\geq 10$                 | 1.5           | 2.3                 |
| 90        | $\geq 20$                 | 1.3           | 2.0                 |
| 90        | $\geq 90$                 | 0.9           | 1.6                 |
| 130       | $\geq 90$                 | 0.9           | 1.5                 |
| 230       | $\geq 90$                 | 2.5           | 3.2                 |

**Notes:** The average extrapolation error is the mean of $[(S_p - S_0)/S_p]$, where $S_p$ is the predicted flux and $S_0$ is the observation. The average error factor is the mean of $S_p/S_0$.

### Table 2

#### Source Count Statistics

| Flux Level (Jy) | 1.4 GHz | 8.40 GHz | 31 GHz | 90 GHz | 230 GHz |
|----------------|--------|---------|--------|--------|--------|
| $S \geq 2.0$   | 846 (546,391) | 190 (190,88) | 88 (88,49) | 49 (49,42) | 24 (24,24) |
| 1.0 $\leq S < 2.0$ | 593 (337,185) | 424 (273,138) | 185 (174,91) | 114 (114,97) | 75 (75,60) |
| 0.5 $\leq S < 1.0$ | 1043 (521,318) | 784 (449,226) | 599 (327,110) | 509 (272,201) | 350 (208,91) |
| 0.2 $\leq S < 0.5$ | 1844 (769,604) | 1685 (703,566) | 1245 (617,97) | 1033 (504,202) | 1033 (480,119) |

**Notes:** Predicted source counts for the full sky are listed at different flux density levels for a number of frequencies. To attain reliable predictions, count statistics were taken in a well-sampled region of the sky void of galactic contamination ($b > 30^\circ$, decl. $> 0^\circ$) and then multiplied by the proper factor to get an estimate for the full sky. Along with this estimate we have listed the counts (A, B), where A is the total number of objects in our entire catalog predicted to fall in that flux interval, and B is the number of objects in our entire catalog observed to fall in that interval (in terms of their average flux for sources observed multiple times). In the case where A was larger than our predicted full sky count derived from a partial region of the sky, we simply pick A as the more representative value.
measurements of the 200 brightest sources. We cannot rule out the existence of an unrelated population of sources peaking around 90 GHz which are not bright at lower frequencies, as 90 GHz observations have only been made for sources selected at frequencies below 10 GHz (this hypothetical source population is limited by GJS). The brightest sources will dominate the anisotropy unless they are masked, because uncertainty in their exact fluxes makes subtraction highly inaccurate. Even after masking, the brightest sources that remain will provide the dominant contribution to anisotropy. An exception to this would be if significant non-Poissonian clustering allowed a large number of dim sources to have a strongly anisotropic distribution. However, Toffolatti et al. (1998) have shown that non-Poissonian clustering is not expected to make an important contribution to the foreground anisotropy from radio sources.

To simulate observations, we convolve all sources on pixelized sky maps (twice oversampled) of resolution varying from 10' to 10 at frequencies between 10 and 300 GHz. The information contained in these sky maps can be used to choose regions for observation (Smoot 1995) and pixels to be masked during data analysis. To avoid underestimating the anisotropy and to reduce the possibility of residual galactic contamination, we use only the portion of each skymap which covers galactic latitudes \( |b| > 30^\circ \) and corresponds to the northern celestial hemisphere to produce estimates of \( \Delta T/T \).

Figure 2 shows a summary of our results for several relevant instrument resolutions. The inverse relationship between anisotropy and FWHM arises due to the combined effects of beam convolution and pixelization. The exact level of oversampling causes a small change in the measured anisotropy, but the 1/FWHM behavior should hold for extrapolation to smaller resolutions (see GJS). The rise beyond 200 GHz is caused by the exponential falloff in CMB antenna temperature beyond 100 GHz. For resolutions as high as 10', a window where foreground confusion should be \( \approx 10^{-6} \) exists around 100 GHz. The contribution to polarized anisotropy of the CMB should be equal to a few percent of the values shown in Figure 2.

We also analyze \( \Delta T/T \) in the northern hemisphere based on only the 758 sources with 90 GHz measurements. The resulting rms \( \Delta T/T \) at 90 GHz with a FWHM of 30' is \( 2 \times 10^{-6} \), which dominates the anisotropy since the rms \( \Delta T/T \) from extrapolating the spectra of the other 1449 sources amounts to only \( 7 \times 10^{-7} \). Hence, of those radio sources that are bright enough at 1.4 GHz to be part of our catalog, we have 90 GHz flux measurements for the majority of sources that will be bright at that frequency. MAP should be able to find any additional populations of bright 90 GHz sources that are too dim at 1.4 GHz to be included in our catalog. Refregier, Spergel, & Herbig (1998) find that the 5 \( \sigma \) source detection limit for 18' MAP pixels will be 2 Jy at 90 GHz. We have 108 sources in our catalog which have been observed to be brighter than 2 Jy at 90 GHz at least once, but only 42 sources have a weighted average flux that high, and a total of 52 sources are predicted to be brighter than 2 Jy at 90 GHz. We therefore estimate that there will be 40–50 radio sources on the sky brighter than 2 Jy at 90 GHz. At the 0.4 Jy level, Toffolatti et al. (1998) predict roughly twice as many sources as we do, but our prediction falls within their range of uncertainty.

Table 3 lists the expected level of anisotropy and the number of detected radio sources in MAP and Planck channels if this type of straightforward 5 \( \sigma \) source detection and

**Table 3**

| Frequency (GHz) | FWHM (arcmin) | Source Detection Limit (Jy) | Number Detected | \( \Delta T/T \) Remaining |
|----------------|---------------|-----------------------------|-----------------|-------------------------|
| MAP            |               |                             |                 |                         |
| 20             | 56            | 1.4                         | 186             | \( 8 \times 10^{-6} \)  |
| 30             | 41            | 1.2                         | 216             | \( 4 \times 10^{-6} \)  |
| 40             | 28            | 0.9                         | 265             | \( 3 \times 10^{-6} \)  |
| 60             | 21            | 1.1                         | 168             | \( 2 \times 10^{-6} \)  |
| 90             | 13            | 1.0                         | 161             | \( 1.5 \times 10^{-6} \) |
| Planck         |               |                             |                 |                         |
| 30             | 33            | 0.9                         | 290             | \( 5 \times 10^{-6} \)  |
| 44             | 23            | 0.8                         | 285             | \( 3 \times 10^{-6} \)  |
| 70             | 14            | 0.6                         | 360             | \( 2 \times 10^{-6} \)  |
| 100            | 10            | 0.6                         | 304             | \( 1.3 \times 10^{-6} \) |
| 143            | 7             | 0.6                         | 323             | \( 9 \times 10^{-7} \)  |
| 217            | 5             | 0.3                         | 533             | \( 7 \times 10^{-7} \)  |
| 353            | 4.5           | 0.2                         | 644             | \( 9 \times 10^{-7} \)  |
| 545            | 4.5           | 0.4                         | 289             | \( 8 \times 10^{-6} \)  |
| 857            | 4.5           | 0.7                         | 125             | \( 4 \times 10^{-4} \)  |

**Notes.** Sources which contribute to the anisotropies at the 5 \( \sigma \) level or higher are considered detected and can be removed by masking the pixels containing them. No attempt has been made to use multifrequency information or further prior information to detect and remove dimmer sources.
TABLE 4
FOREGROUND CONTAMINATION IN 13’ MAP CHANNEL
AT 90 GHz

| Threshold (Jy) | Number of Sources above Threshold | \( \Delta T/T \) |
|---------------|----------------------------------|-----------------|
| None .......... | 0                                | \( 4.4 \times 10^{-6} \) |
| 2 (10 \( \sigma \)) | 49                              | \( 2.1 \times 10^{-6} \) |
| 1 (5 \( \sigma \))   | 161                             | \( 1.7 \times 10^{-6} \) |
| 0.6 (3 \( \sigma \)) | 346                             | \( 1.2 \times 10^{-6} \) |
| 0.2 (1 \( \sigma \)) | 940                             | \( 3.8 \times 10^{-7} \) |

Notes.—This analysis assumes that our catalog is used to identify sources whose fluxes will be above the threshold and that the pixels containing those sources are masked. The result is given in terms of \( \Delta T/T \) due to remaining sources in the northern celestial hemisphere. Our catalog appears to be incomplete beyond the brightest few hundred sources, so the final line is likely an underestimate of anisotropy.

subtraction is performed. Since the 90 GHz MAP channel will in fact have a resolution close to 12’ we expect a 5 \( \sigma \) source detection limit of 1 Jy at 90 GHz. These detected sources represent a list of the few hundred brightest radio sources in the sky at each frequency. The anisotropy levels are shown in Figure 2. Table 4 shows how the expected level of temperature anisotropy from radio sources varies with cutoff level, where we use our catalog to obtain prior information on which pixels are expected to contain sources at a given flux level and then mask those pixels. While all 5 \( \sigma \) pixels can be masked without such prior information if the CMB anisotropies are assumed to follow a Gaussian distribution, it is impossible to remove all 1 \( \sigma \) pixels without crippling the analysis. The actual improvements from masking all pixels expected to contain 1 \( \sigma \) sources may be less than indicated, however, due to the effect of incompleteness in our catalog. It should be possible to fill in this incompleteness using full-sky catalogs at 5 GHz.

It is possible to make a rough derivation of the results in Figure 2 and Tables 3 and 4 using the source counts in Table 2, equations (2) and (4), and the method described in GJS. Indeed, the values in Table 4 agree with those produced by this back-of-envelope method to better than 50%. We have still included these tables for their applicability to future CMB satellites. The calculations used to generate our results are superior to the back-of-envelope approach in that they use the exact predicted N(S) distribution and account for any non-Poissonian clustering of radio sources present in our catalog. Indeed, the agreement between our full results and the back-of-envelope calculation is a confirmation that non-Poissonian clustering is not making a significant contribution to microwave anisotropy produced by radio sources.

Instruments that only observe a small patch of sky can improve upon masking by avoiding the brightest sources entirely. Due to their high angular resolution, radio interferometers will need to perform simultaneous point source subtraction in order to avoid getting swamped by numerous radio sources dimmer than those included in our catalog. Myers, Readhead, & Lawrence (1993) found \( \Delta T/T \sim 10^{-6} \) after simultaneous point source subtraction in a region initially chosen to avoid bright radio sources. Our prediction for a randomly chosen patch of sky at that frequency is a factor of 10 higher; this is consistent with our finding that the brightest known sources dominate the anisotropy.

4.1. Uncertainties

We estimate an overall systematic uncertainty of a factor of 1.5 for our predictions at frequencies less than 100 GHz, increasing to a factor of 3 at 200 GHz and a factor of 5 at frequencies above 300 GHz. Two major sources of uncer-

Fig. 3.—Sky map of our catalog of radio sources extrapolated to 100 GHz and convolved to simulate observation with a 0.5 beam. The color table (thermodynamic temperature fluctuations) reaches a maximum for sources which will be directly detectable by future satellites. The plot is in Galactic coordinates, and we have added the 1770 brightest additional sources from the PMN catalog to equalize the sky coverage. [See the electronic edition of the Journal for a color version of this figure.]
tainty affect these predictions at high frequency: the likelihood that the spectral index will fall off around 100 GHz due to a falloff in each galaxy’s electron energy spectrum and the possibility of appreciable thermal emission from dust in each galaxy contributing at frequencies above 100 GHz. The dashed error band around our 1° predictions in Figure 2 represents the systematic uncertainty in these predictions—it is the same at all instrument resolutions. The uncertainties in our predictions for 5 σ subtraction by MAP and Planck are at least as large as shown for 1° because the best-measured sources have been subtracted.

4.2. Improving Sky Coverage with the PMN Survey

In order to have a roughly isotropic distribution of radio sources, we have added the 1770 brightest sources from the Southern sky Parkes-MIT-NRAO catalog (Griffith & Wright 1993; Griffith et al. 1994, 1995; Wright et al. 1994, 1996) which were not already included in the SGS catalog. These sources have fluxes measured at 4.85 GHz, and some have also been observed at 2.7 GHz allowing for a rough measurement of their radio-frequency spectral index.

Figure 3 shows a skymap (in Galactic coordinates) of our extrapolated/interpolated radio source predictions at 100 GHz after convolution with a 30' beam using HEALPIX. MAP should detect about 200 of these sources at the 5 σ level. The map shows the |b| > 5 cut we made in the PMN catalog to eliminate Galactic contamination and the dearth of sources at the celestial North pole, where radio source observations are difficult. The addition of these PMN sources makes our coverage roughly equal in both hemispheres, making it possible to create a mask for all sources expected to contribute to MAP at the 3 σ level, which is enough to make a significant reduction in radio source contamination versus 5 σ subtraction alone. This corresponds to masking all sources at the maximum of the color table in Figure 3.

5. DISCUSSION

Analysis of bright radio sources indicates that their spectra are complex and cannot in general be categorized into template spectra or single power laws. The results from our analysis of extrapolation errors suggest that our phenomenological approach of fitting a power law to the high-frequency end of each spectrum is a reasonable model to use to extrapolate radio sources to microwave frequencies. Although subject to systematic errors on a galaxy-to-galaxy basis, we expect our overall extrapolation results to be accurate to within a factor of 2 at 90 GHz (barring new source populations).

Our analysis of foreground confusion from extragalactic radio sources indicates that they contribute negligibly to COBE resolution observations of the CMB, consistent with the conclusion of Banday et al. (1996). However, they do become problematic at higher resolution. Our predictions for microwave anisotropy from radio sources represent a lower limit due to the incompleteness of our catalog and the possible contribution from additional undiscovered source populations. We provide a list of the brightest sources on the sky which can be used to mask pixels in future high-resolution CMB observations.4 The contribution of extragalactic radio sources to CMB anisotropy is comparable at 200 GHz to that of bright extragalactic infrared sources (Gawiser & Smoot 1997; Toffolatti et al. 1998). Our current results indicate a valley at around 200 GHz where the anisotropy from radio sources is a minimum; adding in the contribution from infrared-bright galaxies should move that valley toward 150 GHz.

The results of this investigation motivate an expansion of our catalog so that sources which will contribute to anisotropies on the 1 σ level can be masked. It is clear that the current generation of CMB anisotropy experiments must pay close attention to the possibility of radio point source contamination at all frequencies. Masking pixels which contain bright radio galaxies should reduce this foreground to a manageable level.

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3 Available at http://www.eso.org/~kgorski/healpix/.

4 ASCII files containing our predicted fluxes and their uncertainties are available at http://astro.berkeley.edu/wombat/foregrounds/radio.html.

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