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Can CMB Surveys Help the AGN Community?

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Abstract: Contemporary projects to measure anisotropies in the cosmic microwave background (CMB) are now detecting hundreds to thousands of extragalactic radio sources, most of them blazars. As a member of a group of CMB scientists involved in the construction of catalogues of such sources and their analysis, I wish to point out the potential value of CMB surveys to studies of AGN jets and their polarization. Current CMB projects, for instance, reach mJy sensitivity, offer wide sky coverage, are “blind” and generally of uniform sensitivity across the sky (hence useful statistically), make essentially simultaneous multi-frequency observations at frequencies from 30 to 857 GHz, routinely offer repeated observations of sources with interesting cadences and now generally provide polarization measurements. The aim here is not to analyze in any depth the AGN science already derived from such projects, but rather to heighten awareness of their promise for the AGN community.

Keywords: active galactic nuclei; extragalactic radio sources; cosmic microwave background; polarized emission

1. Introduction

In my role as corresponding author, I am presenting this brief paper on behalf of many colleagues on the Atacama Cosmology Telescope (ACT), *Planck* satellite, and South Pole Telescope (SPT) teams. My role is more salesman than scientist. I hope to convince you that extensive lists of extragalactic sources drawn up as a byproduct of programs to map the cosmic microwave background (CMB) are a rich source of data on AGN emission, including polarized emission, at radio and millimeter wavelengths.

I begin by outlining some general features of CMB observations, including the frequency range generally employed, then turn to the catalogues of sources these programs have produced. I then list some potential advantages of these results for the study of AGN statistics, SEDs, and variability. I will also present a few science results, including high-frequency polarization fractions for AGN.

2. Some Methods and Properties of CMB Experiments

Frequency: The main astrophysical limit on the sensitivity of CMB observations is foreground emission from the Galaxy. That cannot, of course, be avoided for all-sky surveys such as that of *Planck*. We can, however, minimize foreground emission by working at frequencies in the range of ~60–150 GHz where Galactic diffuse emission is a minimum. Moreover, we can clean out Galactic synchrotron and dust re-emission by mapping these at lower and higher frequencies, respectively, and using the resulting maps as templates to subtract the foregrounds. In the case of ground-based surveys, atmospheric opacity also limits the range of frequencies available. The control of foregrounds explains the frequent choice of ~90 GHz or ~150 GHz for CMB surveys. In the future, we can expect a wider range of frequencies, extending to lower frequencies and making use of all atmospheric “windows”, e.g., that at ~220 GHz.

Resolution: Primordial density fluctuations leave an imprint on the CMB at angular scales of a few arcmin to a few degrees. Consequently, high angular resolution is not needed for CMB observations. Few extragalactic sources are resolved, and both flux density and polarization fraction reported in CMB catalogues are averaged over the entire source.

Sensitivity: Modern cryogenic bolometric detectors are approaching the quantum limit on sensitivity: hence, the only way to reduce noise in CMB maps is to use large numbers of bolometers.

Current CMB experiments like ACT and SPT now employ arrays of thousands of bolometers in each frequency band. That allows these experiments, despite their relatively coarse resolution, to reach point source detection thresholds of a few millijansky (mJy; see Table 1). *Planck* observations cover the entire sky and at many frequencies (but with only a few detectors at each frequency); consequently, the sensitivity is much lower.

Table 1. Approximate 1σ sensitivity to compact sources (and beam size) for various CMB experiments at mm wavelengths.

Frequency, GHz	Experiment	Approx.	
		Sensitivity mJy	Beam Size arcmin
70	<i>Planck</i>	450	13
95	SPT	2	1.7
100	<i>Planck</i>	250	9.7
143	<i>Planck</i>	160	7.3
148	ACT	1.8	1.4
150	SPT	1.2	1.2
217	<i>Planck</i>	140	5.0
218	ACT	3	1.2
220	SPT	4	1.0
353	<i>Planck</i>	270	4.9

Products: The primary product of all the programs discussed here is a map of anisotropies in the CMB. These maps also typically contain many sources, both AGN and dusty galaxies, as well as clusters of galaxies detected by their Sunyaev-Zel’dovich signature (see Figure 1 for an example). If, as expected, the CMB fluctuations have Gaussian statistics, all of the information contained in the map is also contained in a power spectrum. The observed power spectrum of the CMB anisotropies is in excellent agreement with theoretical predictions of the now-standard cold dark matter (plus

cosmological constant) model [1]. More to the point for this audience, all the CMB programs are in good agreement: calibration between them matches to a precision of a few percent (see [2] for example).

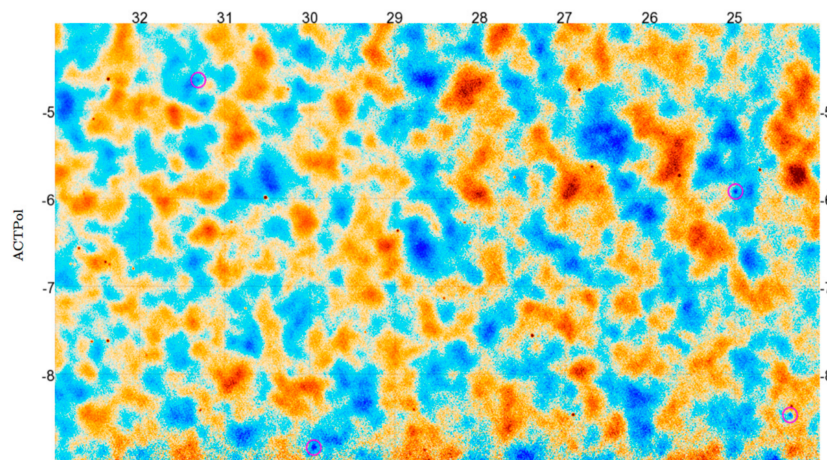


Figure 1. A false-color map of CMB anisotropies (from the ACT team). Several compact sources (AGN and clusters of galaxies) are circled, e.g., in the lower right. A 5×9 degree patch of the southern sky is shown.

3. What Do Such Source Lists Offer?

Between them, ACT, *Planck*, and SPT have catalogued thousands of extragalactic sources. A new list of ACT sources at 148 and 218 GHz will soon appear [3]. *Planck* source lists at each of its 9 frequency bands may be found in <http://pla.esac.esa.int/pla/#catalogues>, with details provided in [4]; in addition, the *Planck* Team is preparing a band-merged catalog of non-thermal sources providing flux densities in nine frequency bands from 30 to 857 GHz [5]. SPT source lists at 95, 150, and 220 GHz are at <https://pole.uchicago.edu/public/data/mocanu13/index.html>; for a fuller description, see [6].

What do these lists offer? First, the surveys that produce them are blind and cover large areas of the sky at fairly uniform sensitivity. Hence, they are useful for statistical studies of AGN. Figure 2 shows source counts at 150 GHz, for instance. Next, the ground-based observations are now quite sensitive; at 150 GHz, for instance, SPT reports 1σ noise of 1.2 mJy. *Planck*, while much less sensitive, operates at frequencies not available from the ground.

A potential problem for the detailed exploration of AGN emission is the relatively poor angular resolution of all of these instruments, as listed in Table 1. At best, the resolution is $\sim 1'$. None (especially *Planck* [7]) resolve sources except nearby ones like M31. As a consequence, when CMB catalogues report polarization, it is the total polarization of the source, summed over any emitting component. This, I suspect, is the main drawback to the use of CMB source lists by the AGN community.

On the other hand, CMB surveys offer simultaneous multi-frequency observations. *Planck* in particular can provide snapshots of AGN SEDs from 30 to 857 GHz at a single epoch (see Figure 3 as an example). New multichroic receivers on the ground-based instruments will offer simultaneous measurements at, say, 150 and 220 GHz in both total intensity and polarization.

Finally, there is the issue of cadence. CMB observations can in principle provide observations of a given source with time separations of minutes to days to years. Figure 3 shows the variable SED of B2251 + 158 = 3C454.3 at four epochs separated by six months, revealing changes in both intensity and spectrum. CMB scientists are just beginning to mine our results for studies of variability in both total intensity and polarization [8,9].

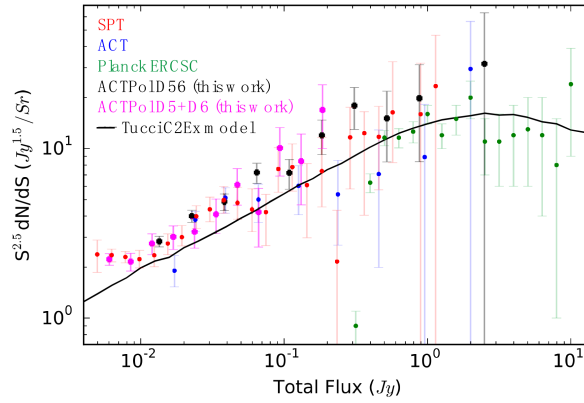


Figure 2. Source counts from CMB experiments at ~150 GHz taken from [10]; new counts will soon be available from [3] as well. Note that the counts run a bit above the model of Tucci et al; see [10].

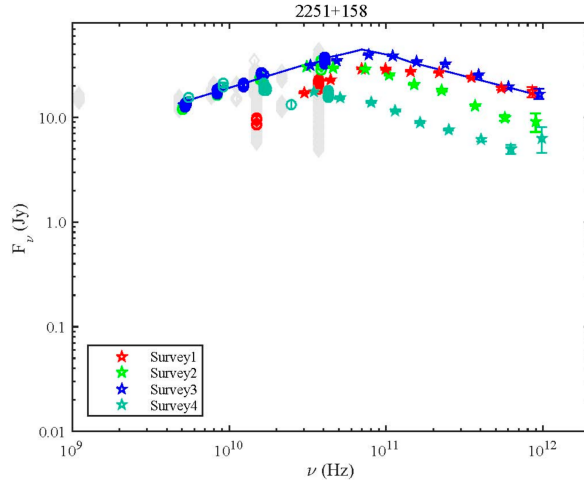


Figure 3. The centimeter to submillimeter SED of a well-studied blazar at four epochs, separated by six months (from *Planck* [7]).

4. Polarization

Planck's receivers at 30–353 GHz are polarized; multi-frequency polarization properties of ~30 bright sources are discussed in [4]; polarization measurements for another ~100 sources at *Planck's* lowest frequency, 30 GHz, are also available there. Statistical information on polarization fraction for a much larger number of *Planck* sources was obtained by stacking *Planck* images [11]. Two conclusions from that paper are as follows: the average fractional polarization of compact sources is approximately constant in frequency (and small) from 30 to 353 GHz (weighted mean = 3%) and the fractional polarization follows a log-normal distribution with $\mu = 0.7$ and $\sigma = 1.0$ (weighted values).

In recent years, both SPT and ACT have added polarized arrays to their instruments, and of course these instruments reach much lower flux densities. Datta et al., [10] for instance, has studied the polarization fractions of about 250 extragalactic sources detected in the CMB intensity (Stokes I) map at 148 GHz made from observations during the first two seasons of the Atacama Cosmology Telescope Polarization (ACTPol) survey, which covers 775 square degrees of the sky. These intensity-selected sources are brighter than 20 mJy in total intensity and are predominantly AGN. Datta and colleagues used simulations to study the robustness of the correction for noise bias, for which they used the Rice distribution. They ran Monte Carlo simulations of the measured quantities to statistically analyze the calculated fractional polarization and the residual bias. When residual bias was taken into account, they found significant detection of polarization in very few of these sources, and no detectable polarization

signal in about 150 sources. They find that the average fractional polarization of the source population is approximately constant with total intensity and well described by a Gaussian distribution truncated at 0, with a mean fractional polarization of $\sim 3\%$. They are essentially fitting for the intrinsic scatter in the fractional polarization of the source population. The best fit model along with the 1-sigma error band is shown in Figure 4. The authors argue that the apparent increase in the fractional polarization with decreasing total intensity is an artifact of the residual bias (reflected in the green band). This work agrees well with the *Planck* findings on brighter sources: the total polarization of AGN is small at high frequencies. For those sources where the luminosity of the jet is dominant, low polarization levels for the jet are also implied.

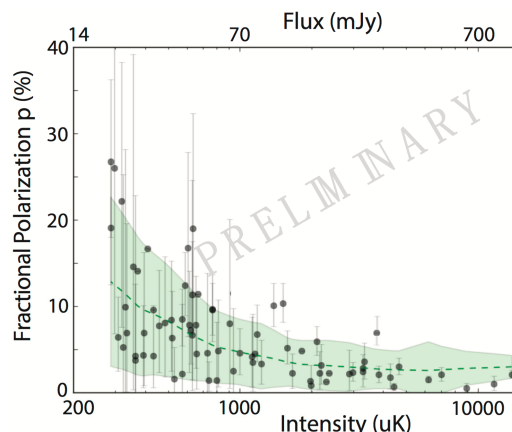


Figure 4. Polarization percentages of ACT sources at 150 GHz as a function of their total intensity. The apparent rise in fractional polarization for weak sources is a consequence of bias, as reflected in the green band derived from Monte Carlo runs. Note that these are *preliminary* results from [10].

In principle, CMB observations can produce values for or upper limits on circular polarization, but this has not been a priority of the CMB community.

I end by expressing the hope that some of the data referred to here will be of use or interest to those of you exploring polarized jets or AGN emission properties more generally.

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Conflicts of Interest: The authors declare no conflict of interest.

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