CMB OBSERVATIONS USING THE SKA

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ABSTRACT

We examine the prospects for observations of CMB anisotropy with the SKA; we discuss the advantages of interferometric SKA imaging, observing strategies, calibration issues and the achievable sensitivity. Although the SKA will probably operate at cm wavelengths, where discrete source confusion dominates the CMB anisotropy, its extreme sensitivity to point sources will make it possible to subtract the source contamination at these wavelengths and thereby image the low surface brightness CMB anisotropies on small angular scales. The SKA, operating at 10-20 GHz, may usefully make high-l observations of the CMB anisotropy spectrum and survey the sky for Sunyaev-Zeldovich decrements.

INTRODUCTION

Observations of the angular anisotropy power in the Cosmic Microwave Background (CMB) temperature fluctuations on different angular scales, leading to a measurement of the power spectrum of the anisotropy, has proved to be very useful in determining the parameters of the space-time structure of the Universe, its constituents, and understanding the ingredients and mechanism for large-scale structure growth and formation. Current goals for CMB research include extending the measurements of the anisotropy spectrum to small multipole orders, measuring the CMB polarization anisotropy, and surveying the sky for CMB decrements that have been created by cosmological clusters via the Sunyaev-Zeldovich effect (SZE). The aims of these observations are to provide additional constraints on cosmological parameters, break parameter degeneracies, probe the cluster evolution and deriving the equation of state for the dark energy.

The CMB anisotropy observations at high multipole orders, of the primary anisotropy as well as of the SZE decrements towards cosmological clusters, are currently being pursued with radio interferometers and bolometric arrays at mm wavelengths. Today, bolometers have the advantage of wider bandwidths and better sensitivity particularly at the mm wavelengths where most CMB telescopes choose to operate in order to avoid the contamination and confusion arising from the non-thermal discrete foreground sources in the sky. However, interferometers have much lower systematic errors and many ground based small angle anisotropy measurements are being done with purpose built interferometers operating at wavelengths around 10 mm. Because recent developments in low noise amplifiers at mm wavelengths have made short wavelength interferometer sensitivities competitive, CMB interferometers operating at 3 mm are being planned.

A consortium of major radio astronomy institutions across the world is currently planning the world's next generation large radio telescope, the Square Kilometre Array (SKA). The telescope will have a total collecting area of 10^6 m^2 and will be capable of interferometric continuum imaging at metre and centimetre wavelengths down to at least 3 cm and perhaps lower. Although the SKA will operate at cm wavelengths, where foreground discrete source confusion limits the achieveable sensitivity for the imaging of the brightness temperature fluctuations in the background CMB sky, its extreme sensitivity due to its large collecting area may make it possible to measure and subtract the point source contamination at these relatively low operating frequencies, and thereby image the low surface brightness CMB anisotropies on small angular scales. We examine the prospects for CMB observations with the SKA in the following sections.

DISCRETE SOURCE CONFUSION

Discrete synchrotron sources in the sky are a foreground 'contaminant' in images of CMB anisotropy. They may be assumed to be Poisson random distributed on the sky with possibly some small degree of clustering. The clustering is indeed tiny: to our knowledge, the NVSS was the first radio survey to detect 2-point angular correlation between radio sources on the sky [1].

The mean spectral index α $(S_\nu \sim \nu^\alpha)$ of extragalactic sources is about -0.7 at metre wavelengths and flattens somewhat to about -0.5 at cm wavelengths: most discrete sources in the sky have lower flux density at smaller wavelengths. Therefore, in images of the sky made with a constant telescope beam, the flux density variations (in Jy beam^{-1}) owing to discrete extragalactic sources are expected to be smaller at shorter (mm) wavelengths as compared to longer (cm) wavelengths. In contrast, at wavelengths longward of about 1 mm, in the Rayleigh-Jeans part of the CMB spectrum, the expected variance in flux density owing to CMB temperature anisotropies in sky images made with a fixed telescope beam increases towards shorter wavelengths as $\Delta S_\nu \sim \nu^2$. Searches for small angle anisotropy that have been done at cm wavelengths, like the 3.4 cm ATCA search for arcmin scale CMB anisotropy [2], were done in fields pre-selected to be relatively devoid of the stronger point sources; however, the sensitivity was limited by confusion due to weaker sources which could not be subtracted because of inadequate sensitivity to these point sources. For this reason, most planned CMB telescopes are being designed for operation at mm wavelengths to avoid the known extragalactic discrete source confusion that dominates the CMB anisotropy at cm wavelengths.

All surveys of the sky for discrete sources, which have covered significant parts of the celestial sphere, have been made at metre and cm wavelengths. Our catalogs of sources detected at mm wavelengths have been made from observations of the mm flux densities of sources detected in the long wavelength surveys. Our knowledge of the source counts in the mm sky is based on extrapolations of source populations identified at cm wavelengths and may miss sources that are bright at mm wavelengths and undetected at cm wavelengths. Recent discoveries of high frequency peakers [3] and sources which have spectral index $\alpha \sim 2$ at cm wavelengths [4] are indications that there may be surprises for us when mm source counts and populations are directly determined via mm surveys. To sumarize, the movement of CMB anisotropy search telescopes to short wavelengths certainly avoids the contamination from most known source populations; however, the mm observations may now have to confront new source populations and ill understood dust contamination. An alternate approach is to make small angle CMB surveys at cm wavelengths and overcome confusion from the well studied cm source populations via high sensitivity detections of these sources.

Relatively nearby sources have differential number counts $N(S) \sim S^{-2.5}$ as expected in a Euclidean universe, weaker distant source counts deviate from this expectation and fall off as $N(S) \sim S^{-1.8}$ because of the space time structure of our expanding universe and source evolution. Normalized to the Euclidean expectation, an upturn is seen in the normalized differential source counts at μJy flux densities because a new nearby population dominates the counts. The differential source counts at μJy flux density levels and at cm wavelengths are approximately

$$N(S) \; = \; 10^2 \; S_{\mu \mathrm{Jy}}^{-2.2} \; f_{GHz}^{-0.8} \; \mathrm{arcmin}^{-2} \; \mu \mathrm{Jy}^{-1}. \tag{1}$$

Any sky survey is made with a certain thermal noise sensitivity and a beam size. There is a threshold flux density S_c at which the integral source count $N(> S)$, at $S = S_c$ and within the beam area, is unity. We expect one source on the average with flux density exceeding S_c in any beam area. If a survey has a thermal noise that is less than or close to S_c, we would expect that sources in the sky which have a flux density well exceeding S_c would stand out and could be reliably identified by the survey as 'foreground sources'. These sources would occupy a small fraction of the image pixels (which I assume are roughly the size of the beam). If these identified sources are subtracted from the image, or if these few pixels that obviously contain sources are omitted from consideration, the weak sources with flux density less than S_c will contribute an image rms of value approximately equal to the flux density threshold S_c.

We would label any survey as being 'sensitivity limited' if the thermal noise in that survey exceeds its S_c; a survey would be considered to be 'confusion limited' if the thermal noise is less than S_c. In images made with a beam of FWHM θ arcmin, the threshold flux density is given by

$$S_c = 40\ \theta^{1.7}\ f_{GHz}^{-0.7}\ \mu\text{Jy}, \tag{2}$$

and the corresponding brightness sensitivity is

$$\Delta T = 14\ \theta^{0.3}\ f_{GHz}^{-2.7}\ \text{mK}. \tag{3}$$

S_c and ΔT are, respectively, the confusion noise limit and corresponding brightness sensitivity limit of the sky survey.

The relatively short baselines of the SKA would be useful for imaging the CMB sky with high brightness sensitivity; we assume herein that CMB images are made with 1 arcmin resolution. At 10 GHz, these images would have a confusion noise of 8 μJy. The corresponding brightness sensitivity limit is 30 μK.

The CMB angular power spectrum is expected to have a band power of $\sqrt{l(l+1)C_l/(2\pi)} \sim 6$ μK on arcmin scales owing to the SZE in cosmological clusters. A SZE survey for distant clusters with the SKA requires lowering the confusion noise via the subtraction of weak sources in every beam area.

The proposed SKA is to have a sensitivity: $A_{eff}/T_{sys} = 2 \times 10^4$ m^2 K^{-1}; we assume a 10 percent observing bandwidth. The entire collecting area (all baselines) would potentially be useful for detecting the discrete source confusion in the fields. We may, therefore, expect the high resolution continuum images made using the full array to have a thermal noise of about 50 nJy with 1 hr integration time at 10 GHz. Placing a 5-σ threshold for the reliable detection of point soucres in the field, we may expect sources with flux density exceeding about 250 nJy to be subtracted. There would be, on the average, about 10^2 such sources in every arcmin area at 10 GHz.

If we assume that all discrete sources above a lower flux density limit of S_m μJy are subtracted from the sky images, the residual confusion rms is

$$\Delta S = 8\ \theta\ f_{GHz}^{-0.4}\ S_m^{0.4}\ \mu\text{Jy}, \tag{4}$$

and the corresponding brightness sensitivity is

$$\Delta T = 3\ \theta^{-1}\ f_{GHz}^{-2.4}\ S_m^{0.4}\ \text{mK}. \tag{5}$$

Assuming that foreground sources above $S_m \sim 250$ nJy are successfully subtracted, the residual confusion in arcmin resolution images may be expected to be as low as 6 μK at 10 GHz.

It appears that the SKA could usefully image the background CMB at a frequency $\gtrsim$10 GHz, with arcmin resolution, and with a confusion noise limit less than 6 μK. If the thermal noise is to be less than the residual confusion noise, say a tenth of the confusion noise, a quarter of the SKA baselines are to be useful in making the arcmin scale CMB survey images.

INTERFEROMETRIC CMB IMAGING WITH THE SKA

Interferometers are the instruments of choice for precision measurements of extremely weak sky signals like the CMB anisotropies because they have much lower systematic errors. The SKA, being an interferometric imaging telescope, would have substantial advantages of lower systematics. The lower element sensitivity, owing to the smaller bandwidths at the longer operating wavelengths, would be offset by the sensitivity gain obtained by the extremely large number of antenna and receiver elements. Additionally, at the longer cm wavelengths, system temperatures are lower owing to lower receiver noise temperatures, lower losses in signal transmission, lower atmospheric emission temperature.

The inherent stability of interferometers implies that highly precise calibration, including polarization calibration, is possible. In some of the SKA configuration solutions, the stations have a large number (n) of elements in compact arrays. These arrays have of order n^2 longer baselines that will resolve the CMB but will measure the discrete sources with high accuracy. Since the same elements measure the long and short baselines simultaneously, the subtraction of self calibrated intensity and polarization should be accurate to better than 1 part in 1,000.

Finally each SKA patch can make an independent observation, and these could either be used to decrease noise in one patch of sky, or to observe patches over a larger area to increase the survey area, in searches for cosmological clusters, or to reduce cosmic variance, in statistical measurements of CMB anisotropy.

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