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WIDE–FIELD EFFECTS IN REDSHIFTED 21 CM POWER SPECTRA

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ABSTRACT

Foreground emission is currently the primary limitation to detection of redshifted Hi emission from the epoch of reionization. Modern radio telescopes that target this cosmological signal are typically wide–field instruments. Through modeling of delay spectra measured between antenna pairs, it has recently emerged that wide–field measurements imprint a characteristic *pitchfork*–shaped signature in this Fourier domain. It is characterized by enhanced power from foreground emission mapped to regions near the horizon and plays a significant role in determining the contamination of the cosmological Hi signal. With MWA data sensitivity improved by coherently averaging snapshots aligned in local sidereal time across different observing nights, we confirm the prediction from modeling at $> 5\sigma$ level.

Subject headings: cosmology: observations — dark ages, reionization, first stars — large-scale structure of universe — methods: statistical — radio continuum: galaxies — techniques: interferometric

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1. INTRODUCTION

2. WIDE–FIELD EFFECTS IN DELAY SPECTRUM

Thyagarajan et al. (2015) have described in detail the effects of wide–field measurements as seen in the delay spectra of interferometer *visibilities*. Here, we give a brief overview of the wide–field signature predicted therein.

The delay spectrum for a baseline vector, $\boldsymbol{b}$, is given by (Parsons et al. 2012a,b; Thyagarajan et al. 2013, 2015):

$$\tilde{V}_b(\tau) \equiv \int V_b(f)\, W(f)\, e^{i2\pi f\tau}\, \mathrm{d}f, \tag{1}$$

with interferometer visibilities, $V_b(f)$, given by (van Cittert 1934; Zernike 1938; Thompson et al. 2001):

$$V_b(f) = \iint\limits_{\text{sky}} A(\hat{\boldsymbol{s}},f)\, I(\hat{\boldsymbol{s}},f)\, W_{\mathrm{i}}(f)\, e^{-i2\pi f \frac{\boldsymbol{b}\cdot\hat{\boldsymbol{s}}}{c}}\, \mathrm{d}\Omega \tag{2}$$

$$= \iint\limits_{\text{sky}} \frac{A(\hat{\boldsymbol{s}},f)\, I(\hat{\boldsymbol{s}},f)}{\sqrt{1-l^2-m^2}}\, W_{\mathrm{i}}(f)\, e^{-i2\pi f \frac{\boldsymbol{b}\cdot\hat{\boldsymbol{s}}}{c}}\, \mathrm{d}l\, \mathrm{d}m, \tag{3}$$

where, $I(\hat{\boldsymbol{s}},f)$ and $A(\hat{\boldsymbol{s}},f)$ are the sky brightness and antenna's directional power pattern, respectively, as a function of frequency (f) and direction on the sky denoted by the unit vector $\hat{\boldsymbol{s}} \equiv (l,m,n)$, $W_{\mathrm{i}}(f)$ denotes instrumental bandpass weights, $W(f)$ is a spectral weighting function that controls the transfer function in the delay transform, $\mathrm{d}\Omega = (1-l^2-m^2)^{-1/2}\, \mathrm{d}l\, \mathrm{d}m$ is the solid angle element to which $\hat{\boldsymbol{s}}$ is the unit normal vector, and c is the speed of light. $\tau = \boldsymbol{b}\cdot\hat{\boldsymbol{s}}/c$ is the geometric delay between antenna pairs measured relative to the zenith and provides a mapping to position on the sky.

In wide–field measurements, the steep rise in subtended solid angle near the horizon for a fixed delay bin size significantly enhances the integrated emission near the horizon delay limits. This is found to be true for diffuse emission even on wide antenna spacings because their foreshortening towards the horizon makes them sensitive to large angular scales that match the inverse of their foreshortened lengths.

Typically, an antenna is most sensitive towards its primary field of view relative to the rest of the sky, which in conjunction with the aforementioned wide–field effects results in a characteristic "pitchfork" signature in the delay spectrum.

Although there is marginal evidence for presence of this feature in the *zenith* snapshot presented in Thyagarajan et al. (2015), the high level of thermal noise prevented a robust confirmation. In this paper, we confirm the *pitchfork* signature using deeper data from the MWA.

3. THE MURCHISON WIDEFIELD ARRAY OBSERVATIONS

The MWA observations and data analysis used in this study are already described in Thyagarajan et al. (2015). In order to reduce thermal fluctuations while maintaining coherence, it is essential to average independent data sets obtained over the same region of sky with identical beamformer settings. Hence, we select a subset of MWA snapshots each of duration 112 seconds obtained over different nights which are aligned to within 72 seconds of each other in *local sidereal time* (LST) around a mean LST of 0.04 hours with the MWA tile beam pointed at zenith. The database contains 14 snapshots satisfying these criteria. Two of these snapshots were found to contain amplitude and phase artifacts for a significant duration across different baselines. Hence, they have been excluded from our analysis.

The delay spectra of the rest of the snapshots were verified to be coherent in their amplitudes and phases. These complex valued delay spectra from independent snapshots are averaged together to lower thermal fluctuations without losing coherence from foreground contributions. The results are discussed below.

4. RESULTS

5. SUMMARY

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REFERENCES

Parsons, A., Pober, J., McQuinn, M., Jacobs, D., & Aguirre, J. 2012a, ApJ, 753, 81

Parsons, A. R., Pober, J. C., Aguirre, J. E., et al. 2012b, ApJ, 756, 165

Thompson, A. R., Moran, J. M., & Swenson, Jr., G. W. 2001, Interferometry and Synthesis in Radio Astronomy, 2nd Edition (Wiley)

Thyagarajan, N., Udaya Shankar, N., Subrahmanyan, R., et al. 2013, ApJ, 776, 6

Thyagarajan, N., Jacobs, D. C., Bowman, J. D., et al. 2015, ArXiv e-prints, arXiv:1502.07596

van Cittert, P. H. 1934, Physica, 1, 201

Zernike, F. 1938, Physica, 5, 785