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Dipole Anisotropy as an Essential Qualifier for the Monopole Component of the Cosmic-dawn Spectral Signature, and the Potential of Diurnal Pattern for Foreground Estimation

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Abstract

While the importance of detecting the global spectral signatures of the redshifted 21 cm line of atomic hydrogen from the very early epochs cannot be overstated, the associated challenges are not limited to isolating the weak signal of interest from the orders of magnitude brighter foregrounds, and extend equally to reliably establishing the origin of the *apparent* global signal to the very early epochs. This Letter proposes a critical dipole test that the measurements of the monopole component of the spectrum of interest should necessarily pass. Our criterion is based on a unique correspondence between the intrinsic monopole spectrum and the differential spectrum as an imprint of dipole anisotropy (DA) resulting from the motion of observer with respect to the rest frame of our source (such as that of our solar system, interpreted from the DA in the cosmic microwave background radiation (CMBR)). More importantly, the spectral manifestation of the DA gets *amplified* by a significant factor, depending on the monopole spectral slopes, rendering it feasible to measure. We describe the details of such a test, and illustrate its application with the help of simulations. The Letter also alludes to a novel model-independent path toward isolating the foreground contribution, using the diurnal pattern readily apparent in drift-scan observations. Such a dipole qualifier for the monopole spectrum, when combined with reliable foreground estimation, is expected to pave way for in situ validation of spectral signatures from early epochs, which are important to presently reported and future detections of Epoch of Reionization (EoR) signal.

Key words: cosmic background radiation – cosmology: observations – dark ages, reionization, first stars – methods: data analysis – methods: observational – radio lines: general

1. Introduction

A number of ongoing and planned future efforts at low radio frequencies aim to detect precious tokens of the yet-unobserved details of the transition from the dark ages to the cosmic dawn and beyond to the completion of reionization, heralded by the first stars (Bowman et al. 2018, and references therein). The potential detectability of a global signal from the redshifted 21 cm line of atomic hydrogen across this cosmic transition was first discussed by Shaver et al. (1999). The detection of such signals holds unmatched promise to reveal several key details of the physical condition and constituents of the universe during these early epochs (see Pritchard & Loeb 2012, and references therein).

Based on their most recent spectral measurement in the spectral range 50–100 MHz, Bowman et al. (2018, hereafter BR3M18, p. 67) reported the "detection of a flattened absorption profile in the sky-averaged radio spectrum." The authors point out the key element of surprise: the depth and flatness of the profile are significantly higher than even the deepest predicted (Cohen et al. 2017). Not surprising is, of course, the nature of the reaction stimulated by this news, which includes not only a burst of communication on the implications of this finding, but also the urgency for competing radiometers globally probing this spectral window to verify, and possibly confirm, the reality of the reported absorption profile.

While appreciating the challenges involved in the detection of signatures from H I-line at these early epochs, it is worth noting that the corresponding monopole component or the so-called global signal—manifested as a faint spectral signature—is considered to be relatively readily detectable, if only the native radiometer sensitivity in the spectroscopic measurements alone were to dictate reliability of the probe (see an early discussion in Shaver et al. 1999). There is little reason to doubt that if the origin of signal reported by BR3M18 indeed corresponds to those early epochs, one would expect a prompt confirmation of the spectral signature to be forthcoming from measurements with other radiometers. However, the converse cannot be stated with matching confidence.

The reasons and the need for due caution have been well appreciated, and stem from the high magnitude and uncertainty associated with contamination or confusion from other potential contributors. The contaminants range from a wide variety of astronomical sources, bright and faint, in the foreground, to a set of systematics and variations traceable to man-made signals or measuring instruments/setup (see Shaver et al. 1999; Pritchard & Loeb 2012; BR3M18; and references in the latter).

Despite all of the careful accounting and removal of the obvious and subtle contributions, there still remains a significant challenge to distill the underlying Epoch of Reionization (EoR) global signal, in the presence of bright foreground emission, even though procedures to fit together a suitable spectral model for foreground and monopole signature have been routinely employed. A reliable way to estimate and separate the foreground contribution is certainly desired.

Ideally, we also require a critical test to reliably verify that the apparent EoR signal (e.g., as in BR3M18 or any future report) is indeed from the early epochs. However, despite an earlier discussion by Slosar (2017, p. 4) on the magnitude of the dipole spectral signature and mention of its potential use to "cross-check measurements derived from the monopole," the dipole spectrum measurements have not yet received its due attention.[1] Interestingly, Slosar (2017, p. 4) has argued in favor of measuring the dipole spectral signature, even if weak, instead of monopole, because the former would be much less contaminated by galactic foregrounds, but also remarked that "one could imagine an experiment that would measure both at the same time."

In this Letter, we propose a dipole-based in situ qualifier that the measured EoR spectra should necessarily pass to be consistent with being a monopole component of the signal from the early epochs, and show how this signature can be measured despite its weakness. This qualifier has the potential to serve as a conclusive test as well, and also to provide a useful reciprocal prediction. We also draw attention to a potentially effective path to estimate and isolate the foreground contamination in a model-independent manner, based on apparent diurnal pattern.

2. Direction Dependence of Apparent Spectrum of the EoR Signal, and the Amplified Diurnal Dipole Imprint

The generally accepted interpretation for the dipole anisotropy (DA) in the cosmic microwave background radiation (CMBR) is the Doppler effect due to the peculiar velocity v of the solar system ($=369.0 \pm 0.9\,\mathrm{km\,s^{-1}}$ toward Galactic coordinates $(l,\ b) = (264^{\circ}.99 \pm 0^{\circ}.14,\ 48^{\circ}.26 \pm 0^{\circ}.03)$; Hinshaw et al. 2009) with respect to the rest frame of CMB (see also Burigana et al. 2018, and references therein), although alternative possibilities have also been discussed (see, for example, Inoue & Silk 2006). We explore below how the associated Doppler effect would manifest in apparent spectral profiles of the much sought-after monopole component of EoR signal.

In general, given the approaching velocity, v, radiation at frequency, ν, reaching from an angle, ψ, with respect to the direction of the velocity, will be shifted to apparent frequency, ν_a, given by $\nu_a = \nu(1 + \beta\cos\psi)\big/\sqrt{1 - \beta^2}$ where $\beta = v/c$, and c is the speed of light. When $v/c \ll 1$, the Doppler shift $\Delta\nu = (\nu_a - \nu)$ will also be proportionally small compared to ν, and can be approximated to the first order as $\nu\beta\cos\psi$. Thus, for an intrinsic EoR monopole spectral profile $\Delta T(\nu)$, the apparent deviation profile (usually in units of temperature), obtained after the careful subtraction of foreground and appropriate calibration (including CMBR dipole variation to avoid its implied amplitude scaling of monopole spectrum, even though small), would be direction dependent (in scaling of its spectral axis) and can be expressed as $\Delta T_a(\nu,\ \psi) = \Delta T(\nu(1 - \beta\cos\psi))$, or, more generally,

$$\Delta T_a(\nu,\ \hat{s}) = \Delta T(\nu(1 - \beta\hat{s}.\hat{s}_{\mathrm{DA}})) \tag{1}$$

where $\hat{s}$ and $\hat{s}_{\mathrm{DA}}$ (or $\mathrm{RA}_{\mathrm{DA}}$, δ_{DA}) are unit vectors in the directions of source and DA, respectively, and "." indicates the dot product of these vectors. A sky-averaged version of the apparent spectrum, when integrated over the full sky (4π sr), the contribution at each ν_a can be shown to be an average of the underlying spectrum ΔT over a window $\nu \pm \nu\beta$, amounting to smoothing by a rectangular spectral window of width proportional to ν. Thus,

[1] Ironically, the author was unfortunately unaware of this paper until after the submission of initial manuscript, which is now revised accordingly, thanks to Ravi Subrahmanyan drawing attention to this paper.

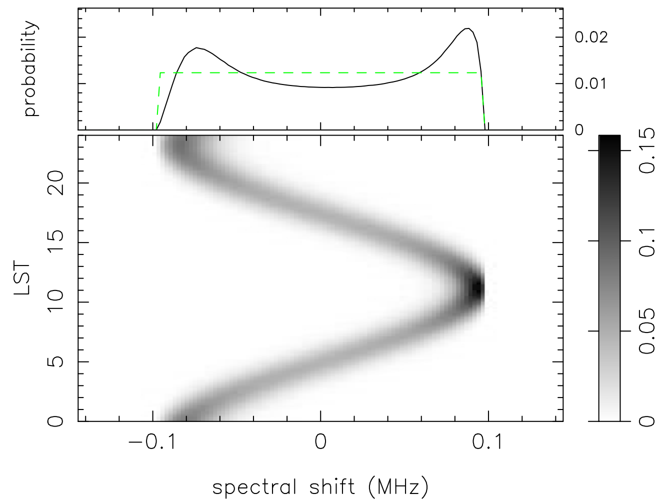

Figure 1. Spectral shifts and spread are shown in grayscale (bottom panel) as a function of Local Sidereal Time (LST). The top panel shows the integrated effect of smearing over the sidereal day, for the transit observation (solid line), as well as for all-sky integration (dashed line).

$$\langle \Delta T_a(\nu) \rangle_{\text{all-sky}} = \frac{1}{2\nu\beta} \int_{-\nu\beta}^{+\nu\beta} \Delta T(\nu + f)df. \tag{2}$$

For $\beta \ll 1$, the smoothing is not expected to be noticeable, except for unlikely sharp features in the underlying spectrum, particularly because there is no net shift or stretching/contraction of the profile, given the symmetry of the window about zero shift.

In practice, even in a snapshot measurement, sky signals (i.e., the associated power spectra) from a range of directions would be averaged over the visible sky, weighted by the instrumental angular response $G(\hat{s})$, or $G(\theta,\ \phi)$ as a function of azimuth ϕ and zenith angle θ, with a nominal pointing center, say, $\hat{p}$, expressible in terms of R.A. (or Local Sidereal Time (LST)) and decl., (RA, δ) or (LST, δ). For radiation at a given radiation frequency ν, the beam-averaging would result in a spread or smear in the apparent ν_a, given by

$$\Delta T_{\mathrm{obs}}(\nu_a,\ \hat{p}) = \frac{\int_\theta \int_\phi G(\theta,\ \phi)\Delta T(\nu,\ \hat{s})\sin\theta d\theta d\phi}{\int_\theta \int_\phi G(\theta,\ \phi)\sin\theta d\theta d\phi} \tag{3}$$

such that $\nu_a = \nu(1 + \beta\hat{s}.\hat{s}_{\mathrm{DA}})$, and the direction $\hat{s}$ is a function of θ, ϕ. Figure 1 shows an example of how such a spread in the shift $(\nu_a - \nu)$ would vary as a function of LST, computed for $\nu = 78.3$ MHz, and assuming meridian transit observations with a 30° (FWHM) beam pointed to the zenith at a latitude of $-26^{\circ}.7$ (chosen to be similar to the observing setup of BR3M18, except that we assume the beam to be frequency-independent, for simplicity). The profile of the spectral spread, or equivalently a smoothing function, also shows significant variation as a function of LST, as expected.

Given an observing band from $\nu_{\min}$ to $\nu_{\max}$, if even the maximum possible shift $\nu_{\max}\,\beta$ is $\ll$ the width of the narrowest feature in the profile, it is easy to see that the residual profile deviation $\delta T_a(\nu,\ \hat{s})$ from the original signal profile $\Delta T(\nu)$, or say, the difference profile, can be expressed as

$$\delta T_a(\nu, \hat{s}) = \Delta T(\nu(1 - \beta\hat{s}.\hat{s}_{\rm DA})) - \Delta T(\nu) \quad (4)$$

$$= -\nu\beta(\hat{s}.\hat{s}_{\rm DA})(d(\Delta T(\nu))/d\nu) \quad (5)$$

$$= -\nu\beta(\hat{s}.\hat{s}_{\rm DA})D(\nu) \quad (6)$$

where $D(\nu) = d(\Delta T(\nu))/d\nu$, the first derivative of the original profile with respect to frequency ν, and

$$\hat{s}.\hat{s}_{\rm DA} = \cos\delta\cos\delta_{\rm DA}\cos({\rm LST\text{-}RA_{DA}}) + \sin\delta\sin\delta_{\rm DA}. \quad (7)$$

The essential origin, and the implied magnitude, of this variation induced by observer motion are no different from that discussed by Ellis & Baldwin (1984), although they are described in the context of apparent source distribution and related parameters. The major difference is that here the so-called "spectral index" is neither small nor "constant," thanks to the expected variations across the spectrum associated with the redshifted H I from early epochs, and the associated spectral slope $D(\nu)$. The relatively rapid and large magnitude changes in $D(\nu)$ not only make the difference profile $\delta T_a(\nu, \hat{s})$ spectrally featureful, but also correspondingly amplify its variation as a function of direction $\hat{s}$ (or LST). In vivid contrast to most of the manifestations of the DA resulting from the solar system motion, being typically of the order of v/c, that is about one part in a thousand, the amplification is found to raise the scale of profile changes by typically an order of magnitude, to a percent level.

We illustrate in Figure 2 how the dipole modulation would reveal itself in the difference profiles across a sidereal day, in an observing setup similar to that assumed in Figure 1. The cases A and B correspond, respectively, to BR3M18 best-fit profile (50–100 MHz) and the much discussed theoretically predicted spectrum up to 200 MHz (the "turning points" data taken from Pritchard & Loeb 2012). The simulated set consists of a dynamic spectrum spanning a sidereal day with 400 time bins, each representing an apparent spectrum associated with an assumed intrinsic spectral profile as shown in the top panel (dashed line), for a time duration of 3.6 minutes per snapshot and integrated over the sky area defined by the angular response of the instrument.

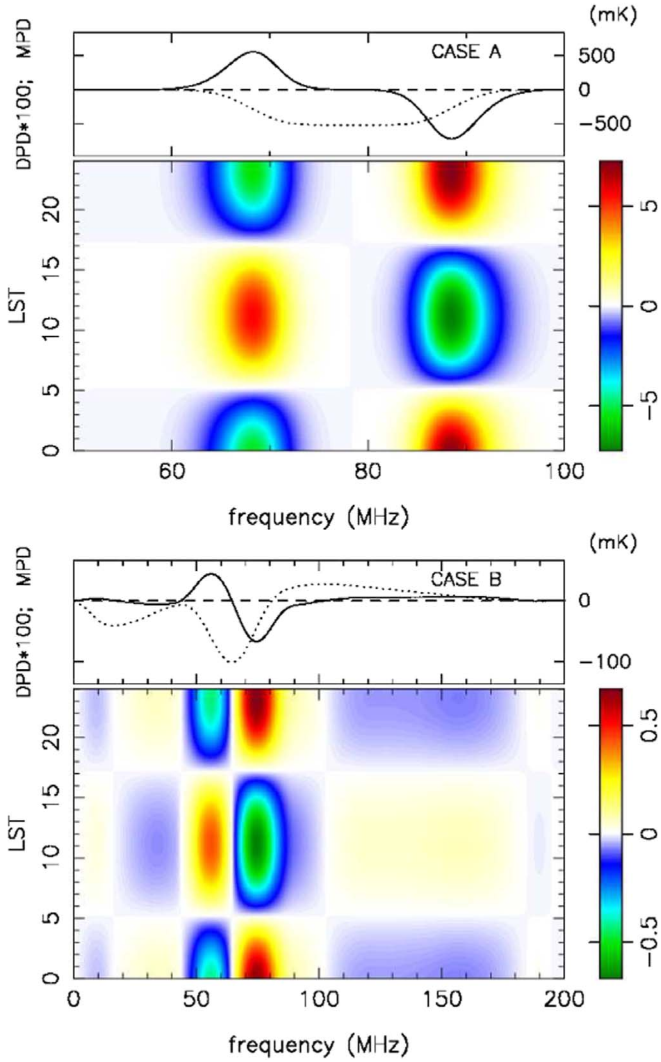

Figure 2. Expected set of residual or difference spectral profiles across the entire LST range, after subtraction of the "all-sky" average spectral profile from the simulated set containing the discussed mild dipole frequency modulation, are shown. The 24 hr cycle and the correspondence with the first (spectral) derivative of the assumed underlying monopole spectrum (of course multiplied by ν, as in Equation (6)), are clearly evident. The amplitude of the co-sinusoidal variation (solid line), after scaling up by 100, is shown in the top panel for each case A and B, along with the assumed monopole spectrum (dotted line).

3. Dipole Qualifier for in situ Validation of the Monopole Component of the EoR Signal

Encouraged by the amplified manifestation of the induced DA in the apparent spectra of the expected monopole signal from the very early epochs, we now proceed to propose a critical in situ test to verify its desired origin.

Here, we assume the usually recommended sky-drift observations made with a fixed beam, for simplicity and preferred coherence in the data set. Such data are assumed to be in the form of an average dynamic spectrum, well-calibrated for system response to the extent possible, and over a span of one sidereal day (averaged synchronously over this period, if from multiple days).

To ensure that the dipole component of the diurnal pattern is devoid of any contamination from a monopole-like contribution (not necessarily limited to the EoR signal),[2] we need to calibrate (divide) the dynamic spectrum by a factor $(1 + \beta\hat{s}.\hat{s}_{\rm DA})$, where $\hat{s}$ corresponds to the RA, and δ of sky transiting at the zenith.

The next step involves well-recognized challenges, wherein the foregrounds are estimated as well as possible and removed. The following processing steps would be obvious to an expert, but are mentioned below merely for completeness.

(a) Averaging the spectra across the entire LST range to obtain the monopole spectrum (though most smeared), as an estimate of $\Delta T(\nu)$, and subtracting it from the entire set of spectra to obtain a set of difference profiles $\delta T_a(\nu_a,{\rm LST})$. (b) Extracting the amplitude profile, $\delta T^{O}_{\rm dp}(\nu)$, at the fundamental frequency of the diurnal variation, using 1d Fourier transforms (FTs) along the LST axis, and rotating the phase to reference it to $\rm RA_{DA}$, or by simply filtering the variation with $\cos\Theta$, to obtain a spectrum potentially containing the dipole signature, as well as with $\sin\Theta$, where $\Theta = 2\pi({\rm LST\text{-}RA_{DA}})/24$ and LST,

[2] Slosar (2017) expression for dipole signature contains this avoidable leakage from the EoR monopole profile.

RA are in units of hour. The latter result, say $\delta T^{O}_{\rm null}(\nu)$, serves as a useful reference profile for assessing uncertainties in the former.[3] When estimated from the original diurnal pattern (without removal of foreground, but after due calibration), this reference profile might serve as a useful initial model of foreground contamination in the *dipole profile*, after appropriate scaling (assessed in the spectral region devoid of expected dipole signature). (c) Using the best-fit profile for the monopole component spectrum, $\delta T^{M}_{\rm mp}(\nu)$, and computing a differential profile (first derivative) times frequency ν as a model profile $\delta T^{M}_{\rm dp}(\nu)$ for the induced dipole component. (d) Finally, cross-correlating or matched-filtering $\delta T^{O}_{\rm dp}(\nu)$ with $\delta T^{M}_{\rm dp}(\nu)$ to assess significance of the match.

Figure 3 illustrates application of the above-mentioned procedure to a simulated set of profiles spanning the entire LST range, and for two descriptions of monopole components similar to those in Figure 2, but now with Gaussian random noise added. The noise level is chosen such that the rms noise in the average monopole profile would be 3 and 0.4 mK for cases A and B, respectively. The extracted monopole and dipole component profiles show the desired correspondence with the respective expected spectra (shown in green) within the noise deviations, which are also found to be consistent with the integration over the entire LST range and across frequency (smoothing function width of 4 and 8 MHz for cases A and B, respectively).

A few key advantages of the suggested method are worth emphasizing. Any time-independent contamination in the apparent monopole spectrum does not contribute to the dipole signature. Hence, the extracted dipole profile can be expected to be free of any error in the model of the monopole profile, and also any effectively additive "local" contributions, such as ground pick up, instrumental noise, and also small multiplicative effects, e.g., remaining systematics from inadequate calibration of instrumental response, residual spectral modulation due standing waves from reflections, etc.

We have assumed that the spectral profile set that we start with is after foreground removal and calibration. However, because (different) foregrounds also will be Doppler modulated differently across the LST, they can potentially contaminate the dipole spectrum of interest, when foreground removal is imperfect. However, residual contribution, if any, from these across the difference spectra would still vary smoothly, and might even be proportional to $\nu\ (1 + \alpha)$ (see Ellis & Baldwin 1984). Given its smoothness, combined with *its presence even in spectral regions devoid of monopole/dipole signal*, the removal of the *baseline* may be possible by modeling with low-order polynomials, or by using models with a few parameters, even allowing for slow changes in the spectral index α with frequency. If the above assumptions are rendered invalid, or if there would be a risk of absorbing the dipole signature in the fits, the following procedure to extract the dipole signature may be employed, once the model profile of the monopole is known and is to be qualified. A 1/0 mask, say $m(\nu)$, corresponding to the zeroes to be expected in the

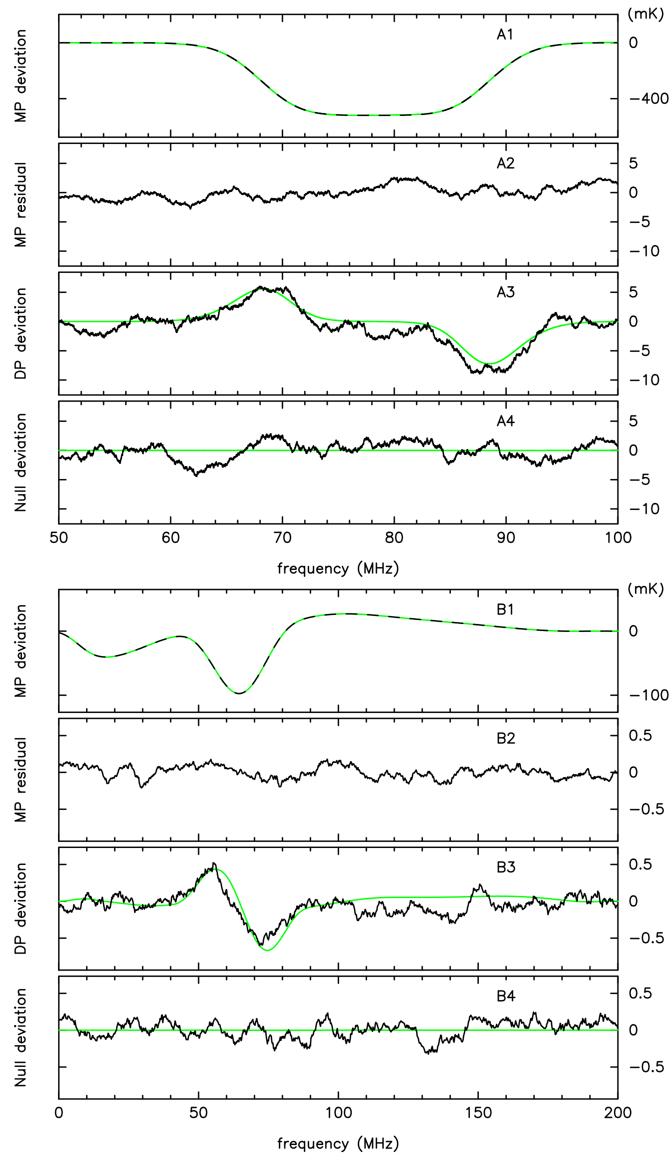

Figure 3. Resultant spectra from the analysis of a simulated dynamic spectrum across the full range of LST, for each of the two monopole profiles considered, cases A and B, are shown separately in the upper and lower halves, respectively. In each half, the top panel (A1, B1) shows an assumed intrinsic spectral profile (green) along with the average of the simulated set of spectra (dashed line), representing an "observed" average profile. These two profiles are indistinguishable on the compressed scale, and hence the difference is separately shown in the panel below (A2, B2). The second panel from the bottom (A3, B3) shows the estimated spectrum of the amplitude of the co-sinusoidal variation across the sidereal cycle referenced to the LST of the dipole (black), along with the expected spectral profile (green). Similarly, the bottom panel (A4, B4) shows a dipole profile extracted with orthogonal modulation, along with an expected null profile, for reference.

implied dipole profile (based on the model monopole profile), and similarly $M(\tau)$ corresponding to the zeroes in the FT of the predicted dipole profile, are noted.[4] An iterative application of these masks in respective domains on successive forward and inverse FTs is expected to converge, resulting in a profile that is consistent with the provided constraints. Such

[3] In what may be a mere coincidence, nonetheless intriguing, the dipole direction is close to the Galactic pole, and hence the transits of the Galactic plane occur preferentially close to the null of the dipole imprint, leading to reduced contamination from any residual foreground due to the plane. In contrast, the reference profile gets almost unattenuated contribution from the plane, and provides a measure of potential contamination in the dipole spectrum.

[4] It is easy to appreciate that the exact relation between the dipole signature and the monopole spectrum continues to hold even for their FTs.

filtering of the associated dipole component benefits from its nulls,[5] which outnumber the order of the polynomial or number of parameters were to be fitted in traditional approach. Note that the locations of these nulls do not change with LST. With profiles at each LST filtered in this manner, we need to look for the diurnal pattern as a test of the expected dipole signature in both frequency and LST together.

The true monopole spectrum is not known a priori, and an apparent monopole spectrum is estimated by averaging the corresponding data across the observing span. It is easy to see that such a monopole spectrum will contain also the contribution associated with the LST-independent term (second term in Equation (7)), defining a tiny leakage of the dipole component in to the apparent monopole spectrum. For $\delta_{\rm DA} \approx -7^\circ$, this leakage is rather small, more so when $|\delta| \ll 90^\circ$, a situation that is preferred in any case for maximizing the dipole modulation as far as possible.

The most exciting prospect is predicting the monopole spectral profile based on extracted dipole spectrum, by scaling the model profile, best fit to the latter, by $1/\nu$, followed by integration. A comparison of this derived version with the observed monopole profile would provide unprecedented scrutiny of the fidelity of the latter, and is likely to be more instructive (relative to the comparison suggested in step (d)), given the relative immunity of the dipole profile to contaminants. How far this exciting prospect can be realized in reality remains to be seen, in light of the known challenges in reliable estimation of the contaminants.

4. On the Prospects of Using Diurnal Variation for in situ Estimation of Foreground

Here, we discuss what can be learned about foregrounds themselves from their significant fraction manifesting diurnal variation apparent in the average dynamic spectrum considered above. This fraction need not be constant across frequency, particularly if the angular response depends on frequency, and for other intrinsic reasons. As already noted, in the FT of the data along time, the sum of monopole signature and average foreground would define the profile of the zero fluctuation frequency, and the immediate FT component[6] at $1/\text{day}$ would contain the dipole component of EoR as well as that of the sky scanned. It is the FT component at $2/\text{day}$ that is free of both the monopole and dipole, and which could provide an estimate of the varying component of the foreground, if the latter were to be only a single peak with a width of fraction of a day, say, $\Delta\text{day} < 1/3$, implying coherence across $1/\Delta\text{day}$ in fluctuation frequency.

In reality, the level of coherence across different FT components (close to zero fluctuation frequency) can be significantly low, limiting their utility for the above purpose. Nonetheless, we can ask if at least the interrelations between the relevant statistical attributes of the varying component would be similar or at least vary smoothly across frequency. The latter is more likely to be true, given the inherent level of smoothness, commonality of origin, and the one-sidedness of the foreground intensity distribution. Note that the possible imprint of the instrumental spectral response will be common to all relevant apparent attributes, and hence would not be expected to affect their interrelation.

We have assessed this expectation through simulations[7] and found that the statistical property, such as the mean intensity and the standard deviation (from the mean), show a reliable degree of correspondence, with their ratio showing only a smooth variation, if any, across frequency, except in the monopole/dipole region. Extensive work would be needed to explore this aspect further; at this stage, we merely wish to draw due attention to this potentially important possibility of in situ estimation of foreground contamination that the statistics and components of observed diurnal pattern might offer.

5. Discussion and Conclusions

In illustrating the application of our method to the model profile of BR3M18, we have deliberately assumed a much reduced rms noise (3 mK) in our simulation (case A) compared to their reported noise rms (~20 mK), in order to aid ready detection visually, resulting in 1 mK rms noise after 4 MHz smoothing. While using cross-correlation or matched-filtering to assess the presence of the dipole component, it worth noting that the sensitivity benefits significantly from the effective bandwidth of the dipole pattern, not limited by the fine resolution of the spectrum. In the present case, this effective bandwidth would be about 8 MHz. It is necessary to stress that for validation of their reported detection using the dipole test, the EDGES (BR3M18) spectra would need an improved signal-to-noise ratio, at least by a factor of about $\sqrt{5}$, for a 3-σ detection of the dipole component of 7 mK, implied by their model monopole profile.

The necessary sensitivities do appear feasible[8] in view of some of the encouraging ongoing efforts (see the list, in BR3M18, of radiometers that can help verify their finding).

Mutual consistency between the observed monopole spectrum and the extracted dipole spectrum thus suggests an essential and unique in situ test that we desire the measurements to pass before the detected signal can be justifiably viewed as from early epochs. When the consistency is high enough, the suggested test has the potential to be a sufficient criterion.

We wish to also point out in passing that the discussed spectral imprint of the DA has interesting reciprocal implications for the signature to be expected across the longitudinal component of the spatial frequency $k_{||}$, relevant to the probing

[5] Samples in the input profile, and its FT, at the locations of these respective nulls (one such amounting to integral of the spectral profile), correspond to foreground alone, and may be used as constraints while modeling the foreground instead.

[6] It is worth pointing out that these Fourier components are the exact equivalent of the visibilities at the various spatial frequencies (namely, u,0) for sky modulated by the system response in declination. Such visibilities represent valuable measurements, which are desirable for the present and other reasons, and are not trivial to measure otherwise from the Earth, without needing to solve for them from interferometric measurements.

[7] More detailed account of the exploration is beyond the scope of this Letter, and will be reported elsewhere.

[8] Although the residual rms (shown in the Extended Data Figure 9 of BR3M18) is seen to depart significantly from the reference expectation (even approaching saturation), the departure appears to be a reflection of required refinement in the presently fitted models (as was the case before inclusion of the 21 cm model). Fortunately, there appears to be no indication of any red process dictating the residuals. While significant refinement in the models, facilitated by a necessary reduction in the random noise, may be anticipated, any errors in the model of the 21 cm monopole and that of the sky-averaged foreground would not affect the sensitivity of detection for the dipole component (except for a corresponding revision, if any, in its profile prediction). Subject to the validity of the above understanding, it would not be surprising if more integration (by a factor of 5 or so) in the measurements of BR3M18 could provide the desired improvement in the sensitivity in order to facilitate the necessary refinement in the modeling of systematics. This refinement would be essential before assessing the possible presence of the dipole signature.

of the statistical signature of the EoR through measurements of spatial power spectrum at low radio frequencies (for example, see Datta et al. 2010 for details on such probes), and would be rewarding to explore.

In the discussion/illustrations so far, we have used the solar system velocity as implied by the CMBR DA as an conservative estimate. It is not known yet if DP anisotropy evolves with redshift, although there have been intriguing indications (see for example, Singal 2011). In any case, the application of our method to dynamic spectrum in ν-LST plane, combined with models for dipole evolution as a function of redshift (i.e., presumably smooth spectral dependence of β, RA_{DA}, δ_{DA}, if any), promises worthy tomographic exploration of the dipole imprint, but only after the primary challenges posed by contaminants are met successfully.

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