Abstract

Observations of the redshifted 21 cm line originating from neutral hydrogen (HI) provide a promising probe of the Epoch of Reionization (EoR) — the era when the first luminous sources re-ionized the diffuse HI in the intergalactic medium. Numerous radio facilities aim to realize this promise by measuring the 21 cm power spectrum (PS), which quantifies the second-order statistics of 21 cm brightness-temperature fluctuations. The bispectrum (BS), the third-order statistic, provides a powerful and complementary probe that captures information missed by the PS. Two major challenges hinder observational measurements of the EoR 21 cm BS: the prohibitive computational cost associated with its high dimensionality, and the overwhelming astrophysical foreground contamination present in the data. The thesis presents the systematic progress in addressing these challenges.

We begin by developing a fast and efficient estimator to compute the binned angular BS (ABS) from radio interferometric observations at a single frequency. The estimator operates on gridded visibilities and leverages the FFT-based acceleration to efficiently compute the ABS, encompassing all possible triangle shapes and sizes. We validate the estimator using simulated visibility data for the Murchison Widefield Array (MWA) observations at $\nu = 154.25$ MHz (redshift 8.2). The estimator faithfully recovers the ABS of the simulated sky signal with $\approx 10\% - 15\%$ accuracy for a wide variety of triangle shapes and sizes across the range of angular multipoles $46 \leq \ell \leq 1320$.

Then, we generalize the estimator for multifrequency observations and present a fast and scalable estimator for the binned multifrequency angular BS (MABS) and the 3D BS, covering all possible triangle configurations. We present the formalism and validate the estimator using simulated visibility data for the MWA observations, which have a bandwidth of 30.72 MHz centered at 154.25 MHz. The BS estimates are obtained for a wide range of triangle shapes covering the scales $0.003 \text{ Mpc}^{-1} \leq k_1 \leq 1.258 \text{ Mpc}^{-1}$. The estimated BS shows excellent agreement with analytical predictions based on the input model BS. We find that the deviations, which are below 20% even in the presence of flagging, are mostly consistent with the expected statistical fluctuations.

Furthermore, employing our estimator on the actual MWA data centered at frequency 154.2 MHz (redshift 8.2), we attempt to measure the EoR 21 cm BS. We find that the 3D cylindrical BS $B(k_{1\perp}, k_{2\perp}, k_{3\perp}, k_{1\parallel}, k_{2\parallel})$ exhibits a foreground wedge, similar to the 21 cm cylindrical PS $P(k_{1\perp}, k_{1\parallel})$. However, the BS foreground wedge, which depends on the three sides of a triangle $(k_{1\perp}, k_{1\parallel})$, $(k_{2\perp}, k_{2\parallel})$, and $(k_{3\perp}, k_{3\parallel})$, is more complicated. Considering various foreground avoidance scenarios, we identify the region where all three sides are outside the foreground wedge as the EoR window for the 21 cm BS. However, the EoR window is contaminated by a periodic pattern of spikes that arises from the periodic pattern of missing frequency channels in the data. We evaluate the binned 3D spherical BS for triangles of all possible sizes and shapes. The measurements are found to be dominated by foreground contamination, even after applying foreground-avoidance techniques.

Finally, we mitigate foreground contamination using the smooth component filtering (SCF) technique. We validate the BS estimation pipeline — including SCF — on simulations and demonstrate that the input BS is reliably recovered for modes above the smoothing scale $[k_\parallel]_f = 0.135 \text{ Mpc}^{-1}$. Applied to actual data, SCF achieves substantial foreground suppression, reducing the amplitude of the cylindrical BS $B(k_{1\perp}, k_{2\perp}, k_{3\perp}, k_{1\parallel}, k_{2\parallel})$ by 3–4 orders of magnitude. The artifacts due to the missing frequency channels in the data are also suppressed. The resulting EoR window is significantly cleaner at small angular modes. We adopt the region $(k_{1\perp}, k_{2\perp}, k_{3\perp}) \leq 0.026 \text{ Mpc}^{-1}$ and $(k_{1\parallel}, k_{2\parallel}, k_{3\parallel}) > 0.135 \text{ Mpc}^{-1}$ to evaluate the 3D spherical BS and constrain the EoR signal. By combining estimates over all triangle shapes, we place the lower and upper limits on the mean cube brightness temperature fluctuations Δ^3. The estimates are consistent with statistical fluctuations from system noise. The most stringent lower limit $\Delta^3_{\rm LL} = -(1.25 \times 10^4)^3 \text{ mK}^3$ and upper limit $\Delta^3_{\rm UL} = (1.22 \times 10^4)^3 \text{ mK}^3$ are obtained at $k_1 = 0.281 \text{ Mpc}^{-1}$. Additional observing time will reduce the noise level and enable substantially tighter constraints on the EoR signal.

The thesis advances the EoR 21 cm BS from a theoretical promise towards a practical observational tool. The techniques presented in this work can be straightforwardly transferred to other radio-interferometric instruments and adapted for investigations of the cosmic dawn and post-EoR era.

Keywords: Reionization; Non-Gaussianity; Observational cosmology; HI line emission; Diffuse radiation; Astronomy data analysis; Radio interferometry; Interferometric correlation