Radio Background Measurements at Long Wavelengths

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Abstract

The measurement of the radio background at long wavelengths has received a great deal of attention in observational cosmology over past decade. The Cosmic Microwave Background (CMB) has imprinted on it the history of the cosmological evolution of the primordial neutral hydrogen. The interaction of the CMB and the neutral hydrogen resulted in 21 cm spin flip transitions that has manifested itself in the form of faint spectral signature and are now redshifted to long radio wavelengths. A successful detection of these signatures requires extremely wideband measurements with a 1:10^5 accuracy that could be accomplished with smart system engineering and accurate theoretical description of the system that is connected to its electrical performance. We herein present the measurement technique and the result of the radio background measurements by a single element experiment "Shaped Antenna measurements of the background RAdio Spectrum" (SARAS). We also present the design and development of a multi element experiment "Hydrogen Probe of the Epoch of REIONization" (HYPERION) for precision measurements of the radio background at long wavelengths.

1. **Introduction**

The study of the cosmic origin and evolution of the Universe has duly received a great deal of attention over the last few decades, addressing the fundamental question of how today's Universe came to exist. The Cosmic Microwave Background (CMB) has showed us a rough picture of how the primordial density fluctuations evolved to large scale structures which gave birth to the first galaxies. The galaxy luminosity function (LF) has been the canonical probe for a direct observation of the early Universe. The Hubble Space Telescope (HST) has brought about enormous progress by providing a sizable sample of galaxies up to redshifts $z \approx 8$. The James Webb Space Telescope (JWST) will probe the early Universe by observing galaxies at redshifts as high as $z \approx 15$. Probing the Universe at even higher redshifts, between the CMB and when the first luminous objects appeared is however limited due to instrumental limitations of even the most powerful space based optical and near infrared telescopes. Hence an important era in the the history of evolution of the Universe, known as the Cosmic Dawn remains unexplored. Questions like - how and when did the first sources form, what was their nature, and how did they influence the growth of the Universe that we live in today, remained unanswered. Of particular importance is the Epoch of Reionization (EoR), an era when the first luminous galaxies ionized the intergalactic medium around them.

An incisive probe of this era is the redshifted 21 cm signal. Spin temperature evolution of the primordial hydrogen through reionization resulted in a 21 cm emission/absorption against the CMB. The first luminous galaxies impacted the spin temperature history of the gas. As a result, the 21 cm signal has imprinted on it the ionization history of the Universe that can tell us how and when the first galaxies appeared, what

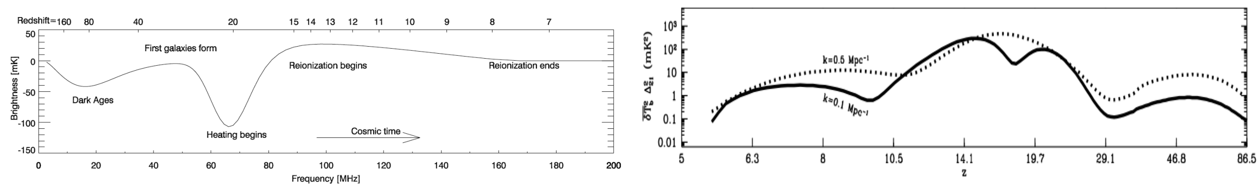

Figure 1: L: Emission/absorption feature of 21 cm monopole as a function of frequency (Pritchard & Loeb 2010). R: 21 cm power spectrum as a function of redshifts (Mesinger, Greig, Sobacchi 2016).

are their properties and how they influenced the structures surrounding them. These signatures are now redshifted to low radio frequencies and can be observed by measuring either the sky averaged redshifted 21 cm signal (monopole) or its power spectrum. The signal amplitude, which is at least five orders of magnitude fainter than the bulk of the radiation background makes the detection of the redshifted 21 cm signal one of the greatest challenges of 21 cm cosmology.

We present the technology and the level of intricacy needed in every step of this extremely challenging measurement through SARAS system performance with identification of the important system performance parameters that is critical to produce a credible measurement (Patra et.al.2013, 2015). We also report our progress towards a wideband measurement of the radio background by the radio interferometer HYPERION.

2. SARAS: An experiment with designed systematic effects

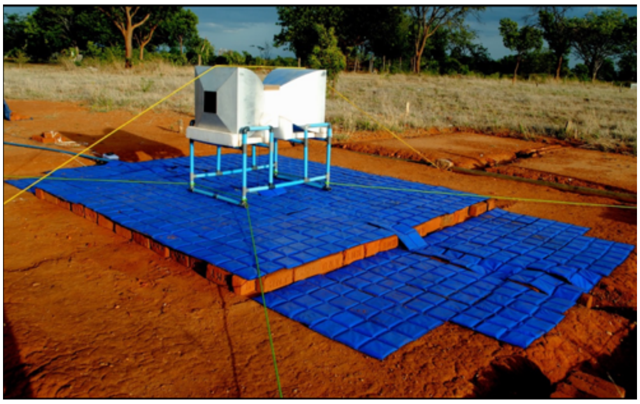

Figure 2: SARAS spectrometer in observing configuration measuring the sky background spectrum between 110 to 175 MHz.

SARAS is a single element radio telescope with a frequency independent antenna, designed, developed and built for the measurement of the radio background at long wavelength.

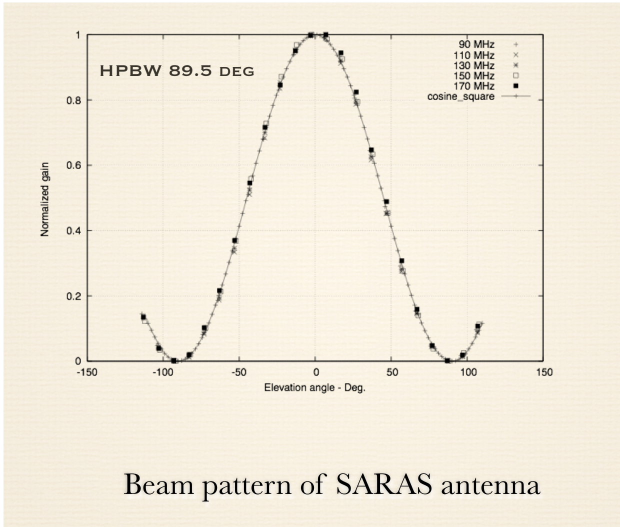

Figure 2: SARAS antenna is a short dipole antenna which with a frequency independent beam pattern between 87.5 to 175 MHz. Simulated and measured performance of the antenna is shown in this figure.

Radio continuum measurements requires total power radio meters that invariably suffer from multiple reflections of the sky noise as well as receiver noise both internally and external to the system. These reflections create the spectral structures that dominates the spectral features that are imprinted on the data. The reflections associated with SARAS system performance are identified and modelled using the electrical parameters of the system. Details of the antenna and the system design and data analysis are presented in Raghunathan et.al.2013, Patra et.al. 2013 and Patra et.al.2015. The key features of the system are,

a.SARAS measures a complex cross-power spectrum whose real part consists of sky

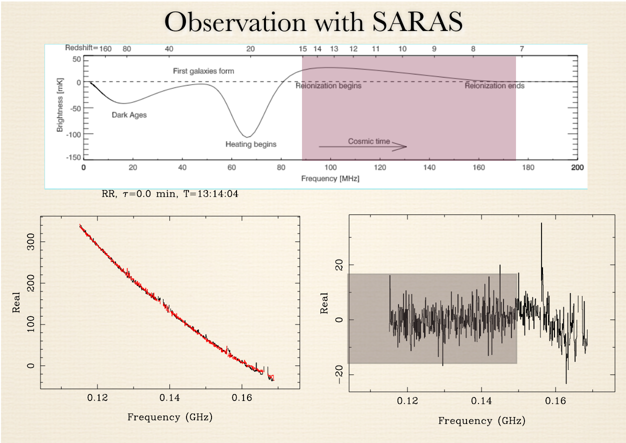

Figure 3: Top panel: The wideband spectral signature imprinted on CMB due to cosmological evolution of the neutral hydrogen. Bottom left: SARAS data (5 mins) jointly fitted with system and sky model. Bottom right: fit residual.

+systematic. Imaginary part consists of systematics alone.

b. Independent and simultaneous measurement of the systematic alone provides independent modelling opportunity to system's electrical parameters while accurately constraining them.

c. All the systematic effects are designed to be additive in nature.

d.Calibration accuracy is >0.06%.

The key results of the SARAS measurements are,

a. The spectral index of the sky and the sky brightness at 150 MHz has been estimated with modelling accuracy >0.5%.

b. Sky measurements reports a steepening of the background spectrum off of the galactic plane.

c. Provided accurate absolute calibration to the all sky maps.

3. HYPERION: An interferometer for measuring the radio background at long wavelengths

Recent work on monopole measurements has shown the potential to measure the radio background spectrum using interferometers (Singh et.al.2015, Presley et.al.2015). In addition, recent constraints from optical observations and its extrapolation to radio frequencies show movement of the EoR spectral signatures to low frequencies (Mirocha et.al.

Figure 4: HYPERION antenna - a double octave bandwidth short dipole antenna with frequency independent antenna beam between 30 to 120 MHz.

2016). HYPERION is an 8 element interferometer being designed and built for measuring the sky continuum background at long wavelengths between 50 to 100 MHz and detecting the spectral signatures from the Epoch of Reionization. The instrument constitutes of a frequency independent antenna which is similar to that of SARAS, scaled to lower frequencies. The measurement consists of 3 data sets including the individual autocorrelations of the antenna, cross-correlation between pairs of antennas and cross power measurements of individual antennas using an interferometric receiver all of which collectively form the data and calibration product. Using absorbers between antennas a spatial variation is introduced to the monopole background as seen by the interferometer.

4.Summary

We present a single element and a multi element experiment SARAS and HYPERION for the measurement of the radio background at long wavelengths. We present the instrumental complexity of this measurement via SARAS system deign and present the results of the SARAS measurements. We present the design concept of the experiment HYPERION interferometer.

5. Acknowledgements

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