Signatures in the Cosmic Radio Background from Spin Flip and Recombination in Cosmological Hydrogen

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Abstract

The cosmological evolution of baryons through recombination and reionization are predicted to manifest as faint spectral features in the cosmic radio background. Pathfinder experiments that aim to detect global phase transitions in the ionization state of the gas in redshifted 21-cm may well be the first radio wavelength constraints on the astrophysics that drive the thermal evolution during reionization and the timing of critical events as first stars and galaxies form. This challenging problem is a motivation for innovative design in radio astronomy receivers. We present progress at the Raman Research Institute in the system design of precision radiometers for detecting spectral deviations in the radio background, design and test measurements of novel antennas, space beam splitters and receiver configurations, and present results from observations to date. The precision radiometer elements developed for the detection of cosmological phase transitions is a step towards building out SKA arrays that operate as interferometers to detect the spatial fluctuations in hydrogen during these critical epochs.

1. Introduction

The last few decades have witnessed substantial progress in our understanding of the cosmological framework of the Universe we live in and of the nature of the initial perturbations that were the seeds for large-scale structure. The progress has been driven by advances in mapping of tracers of the geometry of space-time fabric, tracers of the evolution in the structure in galaxy distributions over cosmic epoch, precision measurements of the cosmic microwave background (CMB) in total intensity and polarization, and substantial refinements in physical models for the fairly detailed evolution of structure from a primordial perturbation spectrum at the inflationary epoch to the present time.

The evolution in the baryons to form galaxies, clusters of galaxies and intergalactic medium structures is considerably more complicated because of the gas dynamics and astrophysical feedbacks that moderate baryon infall. For this reason, there is as yet no firm theory for the thermal history of the gas through the reionization epoch when the first stars and ultra-dwarf galaxies formed. Uncertainties in the populations that provided the first heat input to the primordial neutral gas to elevate the spin flip excitation, and the abundance, luminosities and spectral hardness of the ionization sources in X-ray and UV domains, are what allow a wide range in plausible scenarios. The thermal history of the hydrogen gas---evolution in spin temperature and ionization state---is dependent on the spectral radiance of the first light. The thermal evolution of the primordial hydrogen may be traced by its interaction with the ambient relic radiation and by the emissivity in redshifted 21-cm [1]. This signature of the thermal history, which appears as a distortion in the spectrum of the relic radiation, may be detected by precision measurements of the cosmic radio background.

Such measurements of redshifted 21-cm signatures in the mean spectrum of the radio background might well be the first measurement of the cosmological evolution of the thermal state and excitation of the spin flip of hydrogen gas between recombination and complete reionization. The ongoing efforts by SKA precursor arrays to detect the spatial fluctuations in the ionization during reionization, which would be continued by SKA-Low in its Phase-I and subsequent build out, could be better tailored if useful constraints on the thermal history could be first derived by all-sky measurements of the reionization spectral signatures imprinted on the cosmic radio background.

Redshifted 21-cm reionization signatures are expected in the spectrum of the radio background below 200~MHz, corresponding to a redshift of 6 after which the intergalactic medium is known from QSO absorption studies to be almost completely ionized. Y and μ type distortions in the CMB are other inevitable distortions expected in the radio window; these arise from thermal history of the gas and cosmological structure formation. Recombination of the primeval plasma is also expected to imprint a signature in the radio background in the form of a forest of recombination lines from hydrogen and helium [2] and their detection is a probe of the physics through and somewhat beyond the last scattering surface.

At the Raman Research Institute in Bangalore, India, we have developed methods, system designs and critical components specifically for wideband absolute measurements of the radio background at meter and cm wavelengths. We present herein progress to date towards the detection of cosmological signatures in the radio background.

2. Spectral Radiometer with built in capability for ‘self calibration’

Total-power radiometers inescapably contain a component in their response that originates in the receiver noise of the low-noise amplifiers that are the first active signal processing devices encountered by the faint astronomy signals. Additive systematics generated in the signal path is usually subtracted by switching the receiver between the signal from the antenna and that from a reference load. This provides a differential measurement between the powers from the antenna and load. However, the response to internal systematics does depend on the impedance mismatch at the antenna and, therefore, calibration is compromised when the antenna and load present different impedances. It may also be noted that antenna power, receiver noise and the noise power from any load that is switched into the signal path often undergoes multi-path propagation between their points of origin and the spectrometer backend: this results in ripples in the spectral band.

We have designed a correlation spectrometer configuration called SARAS (for Shaped Antenna measurement of the background RAdio Spectrum) that allows for ‘self-calibration’ of receiver characteristics. The system is designed for operation in the 87.5-175 MHz band. SARAS as deployed in the field is shown in Fig.1 and the system design is depicted in Fig. 2. Details of the system design are in [3] and the design of the fat-dipole antenna is in [4].

Fig. 1. The SARAS fat dipole antenna in the field. Analog receiver is partly in a compact unit between the arms of the dipole and partly below the ferrite tiles covering the ground, RF over fiber runs from the dipole 100 m away to a remote shed that houses further amplifiers and filters that define the band and the digital spectrometer.

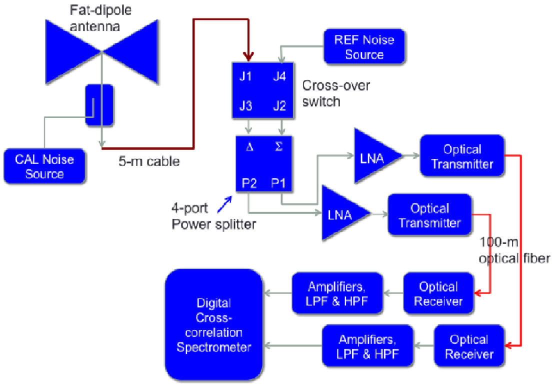

Fig 2. The components of the SARAS system design. The calibration noise source is coupled at the antenna terminals, the receiver unit is 5-m away and buried under the ferrite tiles.

1. SARAS is a correlation receiver, which splits the signal from the antenna up front and prior to the first amplifiers in the signal path, and then computes the spectral energy distribution in the antenna signal as a cross-correlation of the signals in the two split signal paths. The configuration is insensitive to receiver noise.
2. The correlation receiver provides a differential measurement between the antenna temperature and that at the fourth port of the power splitter, which is a differential measurement between antenna and a reference load. Switching receiver noise to calibrate for its additive contribution is difficult; however, the reference load in SARAS is a switchable noise source that enables calibration for its contribution to the response.
3. Calibration noise is injected via a directional coupler that immediately follows the antenna. Calibration noise is switched and the difference spectrum is used for calibrating the off spectrum, which represents the antenna temperature. The switching scheme maintains invariant the impedance match within the signal path.
4. The correlation receiver produces complex spectra; when calibrated with the switched noise the antenna temperature appears wholly in the real part of the spectrum. All noise powers that suffer multi-path propagation appear in both real and imaginary components of the spectrum with identical ripple periods; therefore, solving for their parameters via fits to the imaginary components provides clean constraints on the systematics.
5. Internal additive systematics is canceled by introducing a crossover switch between the antenna signal and the power splitter. The crossover switch alternately connects the antenna to the Σ and Δ ports of the power splitter, and connects the reference termination to the other port. Thus the spectrometer yields antenna minus reference in one switch state and reference minus antenna in the other state. Differencing these gives the desired differential measurement thus cancelling the internal additive systematics, which is the same in both states.
6. Key to reducing the length of multi-path propagation internal to the system is the introduction of RF over fiber in the two signal paths following the power splitter. The RF to optical provides superb reverse isolation. The extremely short path between the antenna and optical modulator avoids multi-path propagations with significant time delays and hence any ripples in the band arising from mismatches would be of fractional order.

A key element in the SARAS system design is the use of a frequency independent antenna of small electrical length. The antenna is designed to be a fat-dipole, with arms shaped to have sinusoidal profile, and short so that the radiation pattern is a cosine-squared form dipole pattern. The antenna is placed above an absorbing ferrite ground plane. Frequency independence is critical so that the modes in temperature structure across the sky do not couple into spectral domain to create modes of spectral ripples, which may be confused with cosmological signatures.

Modeling sky data between 110 and 165 MHz from the SARAS system is well fit with a spectral index −2.46 and normalization 497 K at 150 MHz. SARAS is now being deployed for long duration observations to provide an accurate normalization for long wavelength all-sky maps and for detection of spectral signatures from reionization.

3. A zero-spacing interferometer

2-element interferometers have the advantage that ohmic losses and other additive sources of system noise that originate in the two arms are uncorrelated and hence do not appear in the response when the antenna signals are correlated. However, interferometers are insensitive to any uniform sky and hence are incapable of measurements of the mean cosmic radio background, its spectrum, and cosmological signatures embedded in this background. We have ventured to develop a novel interferometer that has the advantages of being insensitive to internally generated noise power and also responds to the mean sky background. We call our configuration a Zero-spacing interferometer. The configuration consists of a resistive sheet placed between a pair of antennas that form a 2-element interferometer. As shown in Fig. 3, the resistive sheet serves as an electromagnetic space beam splitter. The response of this interferometer to the mean sky background depends on the fractional beam solid angle of the antennas that is filled by the resistive sheet. In Fig. 4 is shown a resistive sheet constructed to validate the principle.

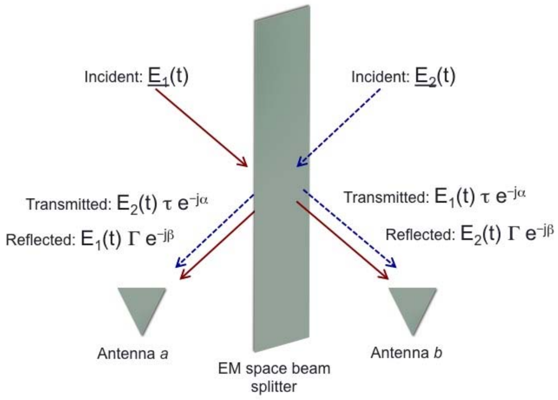

Fig. 3. Sky radiation is incident on both sides of the resistive sheet and propagates to the two antennas as transmitted and reflected components. Each antenna signal has components of radiation incident from the two sides and their cross correlation responds to the mean sky background.

Fig. 4. Prototype resistive sheet built as a soldered square grid of resistors for field measurement of transmission and reflection coefficients.

Our analysis [5] shows that the space beam splitter placed between the pair of antennas needs necessarily to be a resistive sheet, with sheet impedance equal to half the impedance of free space, for maximum response to the mean sky. The resistive sheet transmits a quarter of power incident on any side, reflects a quarter and half the incident power is absorbed. A resistive sheet is frequency independent giving the system a uniform gain over frequency. Further, a square soldered grid of resistive wire or a soldered grid of conductors in which a resistance is introduced in series in every segment may form a resistive sheet in practice. The resistance of each segment is required to be 377/2 Ω. We have constructed such a resistive grid of 3x4 m^2 size and measured the transmission and reflection coefficients and verified that it does indeed perform as required and anticipated from analytic computations. The resistive grid is frequency independent as long as the grid cell size is a fraction of the wavelength. This development continues towards designing an appropriate antenna; we call this project ZEBRA for Zero-spacing measurement of the background radio spectrum.

4. An array for the detection of spectral ripples from the Epoch of recombination

Hydrogen recombination at redshift z=1100 imprints a forest of recombination lines across the radio spectrum, which appear as a tiny additive modulation of the foreground. The adjacent hydrogen recombination lines blend because recombination is stalled and, therefore, the spectrum is expected to appear as a sinusoidal ripple riding on the relatively smoother foreground. We have examined the considerations that go into designing a system for the detection of these transitions and the signal to noise ratio, taking into account the predicted line intensities, foreground brightness, receiver technology, and arrived at the conclusion that detection is indeed possible with a 128-element array of precision spectrometers operating in the 3-6 GHz octave band. A simulation with realistic foregrounds, including calibration processes and implementing an algorithm that removes a smooth foreground demonstrates that it is possible to extract the recombination spectrum in this octave band [6]. The predicted line intensity [2] in the 1-10 GHz band is shown in Fig. 5 and in Fig. 6 we show the form of the recovered recombination spectrum in the 2-6 GHz band following the fitting and subtraction of a smooth function to the measured data. The peak antenna temperature in the line is 10 nK.

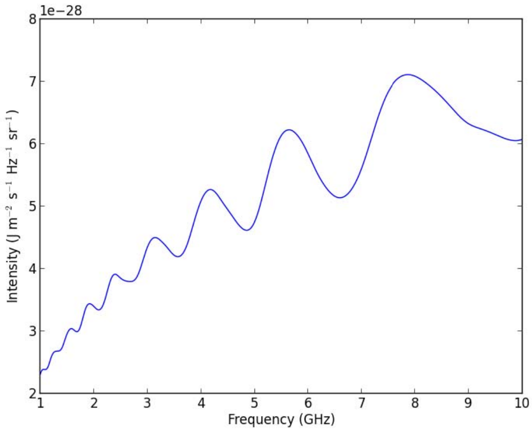

Fig. 5. Computed intensity of the recombination line spectrum in the 1-10 GHz band.

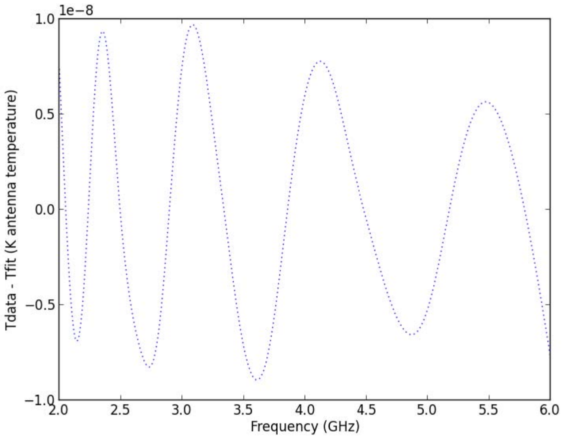

Fig. 6. Expected residual following removal of a smooth fit to the calibrated sky spectrum in the 2-6 GHz band.

A project building a prototype element in the 2.5-5.0 GHz band that consists of a wideband fat monopole antenna coupled to a receiver chain and digital spectrometer is on at the Raman Research Institute.

5. Summary

The challenging goal of detecting faint and wideband spectral features from cosmological evolution in the thermal state of the baryons through recombination and reionization has driven recent progress in radiometer technology. We present recent progress at the Raman Research Institute in the design of receiver configurations that are designed to self-calibrate spectral structures arising from self-generated receiver noise, wideband frequency independent antennas, and space beam splitters of resistive sheets constructed as resistor grid arrays. All these innovations are purpose built as elements of precision radiometers. We present engineering test and measurement results from prototypes as well as results of astronomy measurements of the cosmic radio background from field deployments at remote sites.

6. Acknowledgements

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7. References

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