Enhanced Global Signal of Neutral Hydrogen Due to Excess Radiation at Cosmic Dawn

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Abstract

We revisit the global 21 cm signal calculation incorporating a possible radio background at early times, and find that the global 21 cm signal shows a much stronger absorption feature, which could enhance detection prospects for future 21 cm experiments. In light of recent reports of a possible low-frequency excess radio background, we propose that detailed 21 cm calculations should include a possible early radio background.

Key words: cosmology: theory – dark ages, reionization, first stars – early universe – methods: analytical – radio continuum: general

1. Introduction

The redshifted 21 cm emission, due to the transition between the triplet and singlet states of neutral hydrogen, is an important probe of the high-redshift universe. Unlike the cosmic microwave background (CMB), the 21 cm emission maps the three-dimensional distribution of neutral hydrogen. It contains both spatial and spectral information, leading to experimental approaches focused primarily on the spatial fluctuations or primarily on the sky-averaged spectrum. The latter is the so-called global 21 cm signal, which is an important cosmological probe of the epoch of reionization (EoR; Shaver et al. 1999; Furlanetto 2006).

The 21 cm spatial fluctuations have been extensively studied theoretically (Furlanetto et al. 2004; Morales & Wyithe 2010), but this faint signal is yet to be detected, largely due to very bright foreground contaminants, such as Galactic synchrotron, supernovae remnants, free–free emission and radio point sources (Furlanetto et al. 2006). Many experiments, such as the Low-frequency Array (LOFAR; van Haarlem et al. 2013), the Square Kilometre Array (Koopmans et al. 2015), the Murchison Widefield Array (Lonsdale et al. 2009) and the Hydrogen Epoch of Reionization Array (HERA; DeBoer et al. 2017), are designed to study the 21 cm signatures and foreground mitigation strategies have been proposed making use of the smooth spectral behavior of foregrounds.

The global 21 cm signal may enable a first detection of signatures in the dark ages; only a small amount of integration time (∼O(10²) hours) is required to reach a sufficient detection sensitivity, while interferometric arrays designed for 21 cm fluctuation measurements, such as LOFAR, would require significantly longer integration time. There are difficult calibration problems, but a single-dipole experiment can be constructed to probe the global 21 cm signal. A few projects including the Dark Ages Radio Experiment (DARE; Burns et al. 2012), the Experiment to Detect the Global Epoch of reionization Signature (EDGES; Bowman & Rogers 2010), the Large-Aperture Experiment to Detect the Dark Ages (LEDAs Greenhill & Bernardi 2012) and the Long Wavelength Array (Henning et al. 2010) may be able to detect the global 21 cm signal. However, substantial challenges still exist for the global 21 cm signal measurements. Aside from what is shared with the fluctuation measurements, the ionospheric reflection can generate a contaminating power that may be two to three orders of magnitude higher than the global 21 cm signal (Datta et al. 2014; Vedantham et al. 2014). A mathematical formalism for isolating these foregrounds has been established (Liu et al. 2013) and the separation of the global 21 cm signal is aided by low-resolution spatial information. A Bayesian inference technique was also devised to isolate the foregrounds from the raw signals (Burns et al. 2017).

On the other hand, a space mission like DARE (Burns et al. 2012) could sidestep some issues such as atmospheric contaminant and terrestrial radio frequency interference. With current techniques, foregrounds such as Galactic synchrotron and free–free emission, while orders of magnitude brighter than the 21 cm signal, can be possibly separated from the data and detection of the global 21 cm signal could be achieved by these dedicated experiments.

The characteristic peaks and troughs of the global 21 cm signal are rich in astrophysical information, especially heating mechanisms and ionizing sources. It is believed that gas heating in the early universe mainly comes from accreting black holes and the first stars. The locations of the troughs can differentiate metal-free primeval stars from metal-rich ones (Burns et al. 2017), extra heating due to dark matter annihilation can reduce the absorption trough significantly (Valdés et al. 2013), and warm dark matter, which suppresses structure formation, can delay the absorption feature in the global 21 cm signal (Sitwell et al. 2014).

Numerical simulations have shown that the redshift evolution of the power spectrum of the brightness spatial fluctuations at fixed angular scales resembles that of the global 21 cm signal, although spatial fluctuations are roughly one order of magnitude fainter than the monopole (Santos et al. 2008). There is a possibility that the fluctuation experiments with interferometric arrays could be used to study the global signatures, but extracting a global 21 cm signal from fluctuation experiments with interferometric arrays has not been thoroughly investigated.

The brightness temperature fluctuation is set by the difference between the spin temperature of the hydrogen gas and the temperature of the local radiation field at the 21 cm frequencies. It is usually assumed that the radiation field is dominated by the CMB. Recently, a balloon-borne double-nulled instrument called the Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission (ARCADE 2) detected excess radio radiation, revealing a strong radio radiation
At the time of submission, we were not aware of the pending EDGES result (Bowman et al. 2018), which subsequently reported a measurement of excess 21 cm absorption. Several interesting theories have since been proposed as sources of excess radio radiation at high redshift (Ewall-Wice et al. 2018; Mirocha & Furlanetto 2018; Pospelov et al. 2018).

Figures 1. Radiation excess detected by ARCADE 2. The red solid line represents a CMB radiation field, while the green dashed line shows a significant deviation at $\nu < 1$ GHz. These low frequencies are relevant to the signatures coming from high redshift. The gray region denotes the uncertainty of the excess model in Equation (1).

background, consistent with CMB radiation at high frequencies but significantly deviating from a blackbody spectrum at low frequencies (Fixsen et al. 2011). This radiation is substantially larger than expected from observed radio counts (Singal et al. 2018). It is possible that some of this radiation could originate from early times, such as radio-loud quasars, which have been recently studied (Bolgar et al. 2018). Also, previous works showed that the early radio background could be produced by other sources, such as active galactic nuclei (AGN) around the Cosmic Dawn (Ewall-Wice et al. 2014), supernovae explosions of super-massive stars (Biermann et al. 2014), annihilations or decays of weakly interacting massive particles in extragalactic halos (Fornengo et al. 2011), and CMB spectral distortions caused by photon injection (Ali-Haïmoud et al. 2015; Chluba 2015). Excess radiation at early times at radio wavelengths can change the evolution of the spin temperature and also provide an enhanced background against which absorption can be observed. This suggests that a correction to the spin temperature of neutral hydrogen may be required at high redshift and new features of the global 21 cm signal are possible. If neglected, the predicted intensity of the global 21 cm signal could be underestimated. In this work, we revisit the calculation of global 21 cm signal with a possible high-redshift radio radiation field and discuss the implications of the new features for the global 21 cm signal.

2. Observational Radio Radiation
   Excess Detected by ARCADE 2

The detected ARCADE 2 excess has been fitted by a simple power law, shown in Figure 1. It is seen that the radiation is dominated by the CMB at high frequencies but there is a substantial radio background that dominates at lower frequencies. The radiation excess is fitted with a simple power law as

$$T(\nu) = T_{\text{CMB}} + \xi T_{R} \left(\frac{\nu}{\nu_0}\right)^\beta,$$

(1)

where the CMB temperature is $T_{\text{CMB}} = 2.729 \pm 0.004$ K, normalized to $T_{R} = 1.19 \pm 0.14$ K at a reference frequency $\nu_0 = 1$ GHz, with a spectral index $\beta = -2.62 \pm 0.04$. The measurement errors of the excess have been propagated to the model, and the errors were contributed by the absolute thermometer calibration, thermal gradients of the calibrator, in-flight oscillations and excessive noise, possible drifts of the instrument gain and offsets, uncertainties of Galactic emission subtraction, and uncertainties of the instrument and atmosphere emission (Fixsen et al. 2011). The second term on the right-hand side is the excess radiation (Singal et al. 2018). The excess fraction $\xi$ is set to be unity (Fixsen et al. 2011) but given the fact that radio source counts can contribute to the background, we consider the excess fraction at early times as a free parameter. The excess can not be easily explained by Galactic emission, unresolved emission from the known radio point source population or CMB spectral distortions. The flatter spectrum of the detected excess differentiates it from radio point sources that have a much deeper spectrum (Seiffert et al. 2011). Among other possibilities, some of this excess could also originate from high redshift. Because of the steeply rising spectrum toward longer wavelengths, a significant amount of this radiation that has been redshifted from early times would be substantially larger than the CMB contribution at a rest wavelength of 21 cm at high redshift.

3. Modified 21 cm Global Signal

In this section, we derive the calculations of the global 21 cm signal in the presence of an excess radio radiation field. The global signal is modeled as

$$\delta T_{b} = 27 \lambda_{H I} \left(1 - \frac{T_{s}}{T_{R}}\right) \frac{1+z}{10} \frac{0.15}{\Omega_{m} h^2} \frac{0.023}{\Omega_{b} h^2} (\text{mK}),$$

(2)

where $\lambda_{H I}$ is the wavelength of the Lyman-$\alpha$ transition, and $T_{s}$ and $T_{R}$ are radiation and spin temperatures, respectively. We use the latest Planck parameters for the dark matter ($\Omega_{m}$) and baryonic matter density ($\Omega_{b}$) fractions (Planck Collaboration et al. 2016). Also, the variable $T_{s}$ is replaced by the fitted model in the last section and $\nu = \nu_{H I}/(1+z)$ with $\nu_{H I} = 1420$ MHz.

The spin temperature $T_{s}$ is coupled to the gas temperature $T_{K}$ by collisions and by the Wouthuysen–Field effect (Wouthuysen 1952; Field 1959). It is described as

$$T_{s}^{-1} = T_{R}^{-1} + x_{\alpha} T_{\alpha}^{-1} + x_{\gamma} T_{K}^{-1},$$

(3)

where $T_{\alpha}$ is the color temperature of radiation around the Lyman-$\alpha$ transition, and $x_{\alpha}$ and $x_{\gamma}$ are WFE and collisional coupling coefficients, which both follow a simple scaling $\propto T_{s}^{-1}$ (Pritchard & Loeb 2012). We run 21cmFAST\footnote{https://github.com/andreimesinger/21cmFAST} to create three-dimensional simulations for a few fields such as the
ionizing fraction $x_i$, $x_c$, and $x_o/T_o$ (Mesinger et al. 2011), and we use spatially averaged quantities associated with these fields to derive the spin temperature. In Figure 2, we show detailed calculations of spin temperature, gas temperature, and radiation temperature from redshift $z = 4$ to 30 in solid and dashed lines, corresponding to no radiation excess and an excess corresponding to 10% of the background today being in place at early times, respectively. The gas ($T_g$) temperature may depend on the CMB at early times through Thomson scattering but will not be strongly affected by the relatively small amount of energy in the nonthermal radio radiation field.

As an approximation, we assume both $T_o$ and $T_k$ are independent of the excess radiation field. We substitute the radiation field $T_r$ in Equation (3) by the fitted model of the excess in Figure 1, in this case reducing the excess to only 10% of the observed value to account for possible contributions from low redshift. The coupling coefficients $x_o$ and $x_c$ are modified via a simple scaling $1/T_r$ and the new spin temperature in Equation (3) is derived for this new radiation field.

4. Results and Discussions

The spin temperature with 10% of the excess is shown in Figure 2. We obtain the modified 21 cm global signal according to ARCADE 2 excess in Figure 3. A deep trough with a temperature $\sim 1.1$ K can be detected around $\nu = 90$ MHz (Figure 3 (bottom)). It is apparent that if 10% of the radio background observed today is in place at early times, it will have a large effect on the global 21 cm signal. Furthermore, even 0.1% of today’s background would be enough to produce an observable effect.

In Figure 3 (top), it is seen that the strong coupling between the radiation field and the spin temperature remains unperturbed in the dark ages, but the first trough associated with the formation of first galaxies is altered significantly. The excess radiation can shift the peak of the trough to a lower redshift, but the enlarged difference between the radiation field and the spin temperature due to stronger heating gives rise to a deeper absorption trough with an amplitude $\sim 7$ times higher (assuming 10% excess). As a consequence, the reionization due to ultraviolet radiation is also delayed because of the substantially higher radiation temperature of the 21 cm transition.

Due to instrumental frequency coverage and sensitivity, the absorption trough may be the easiest and the most important feature to be detected from the global 21 cm signal. With the enhanced absorption features in the global 21 cm signal, the detection of the global 21 cm signal would be made significantly easier.

From a 19-minute effective measurements of the LEDA experiment, a $-890$ mK lower limit on the amplitude of the absorption trough is placed between 50 and 100 MHz (Figure 3 (bottom); Bernardi et al. 2016). From observations within a few hours, the EDGES$^6$ experiment found that the residual spectrum, which is foreground subtracted, has a 17 mK r.m.s. limit.

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$^6$ The new EDGES result (Bowman et al. 2018) would require 1.5% of the ARCADE 2 excess to be in place at early times, but making more precise statements requires careful modeling along the lines done in (Ewall-Wice et al. 2018; Mirocha & Furlanetto 2018).
over 90–190 MHz (Monsalve et al. 2017). Both limits require the excess radio fraction of high-redshift origin to be very small.

The fluctuations of the brightness temperature can be split into temporal $\delta T_b(z)$ and spatial $\delta(r)$ components, according to the definition. The average of the spatial part $\langle \delta(r) \rangle$ is zero and the power spectrum $P(k)$ of the spatial part can be calculated by $21\text{cmFAST}$. Here $r$ denotes spatial coordinates. Any spatial fluctuations in both the radiation and brightness temperature fields are absorbed in the power spectrum $P(k)$. Therefore, the spectral information of the sky-averaged signal can also be drawn from the brightness temperature fluctuations at certain angular scales. The black curve in Figure 4 is taken from $21\text{cmFAST}$ simulations (Santos et al. 2008) and is the fluctuation power spectrum with no radiation excess. Based on this power spectrum and the scaling relations revealed by Figure 2, we can further derive two additional power spectra with 0.1% and 10% radiation excess. The predicted strengths of the fluctuation power at $z = 8.4$ are well below the recent limit from the Precision Array for Probing the Epoch of Reionization, leaving a broad parameter space for the excess fraction (Ali et al. 2015).

In this Letter we have investigated the impact of an excess radiation field on the global 21 cm signal, which is found to be significantly amplified, especially in absorption. We find that this key feature can be an order of magnitude stronger than expected, and would be easily detected. Future experiments, such as the DARE and the EDGES (Bowman & Rogers 2010), will be able to examine this enhanced global signal.

Figure 4. Redshift evolution of brightness temperature fluctuations at $k = 0.19 h/\text{Mpc}$. The power of the fluctuations is defined as $\Delta^2(k) = k^3/2\pi^2P(k)$ and $P(k)$ is a three-dimensional power spectrum of the brightness temperature fluctuations.