Astrophysical radio background cannot explain the EDGES 21-cm signal: constraints from cooling of non-thermal electrons

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ABSTRACT

Recently the EDGES (Experiment to Detect the Global Epoch of Reionization Signature) experiment has claimed the detection of an absorption feature centered at 78 MHz. When interpreted as a signature of cosmic dawn, this feature appears at the correct wavelength (corresponding to a redshift range of \( z \approx 15 - 20 \)) but is larger by at least a factor of two in amplitude compared to the standard 21-cm models. One way to explain the excess radio absorption is by the enhancement of the diffuse radio background at \( \nu = 1.42 \text{ GHz (} \lambda = 21 \text{ cm)} \) in the rest frame of the absorbing neutral hydrogen. Astrophysical scenarios, based on the acceleration of relativistic electrons by accretion on to supermassive black holes (SMBHs) and by supernovae (SN) from first stars, have been proposed to produce the enhanced radio background via synchrotron emission. In this Letter we show that either the synchrotron or the inverse-Compton (IC) cooling time for such electrons is at least three orders of magnitude shorter than the duration of the EDGES signal centered at \( z \approx 17 \), irrespective of the magnetic field strength. The synchrotron radio emission at 1.42 GHz due to rapidly cooling electrons is \( \sim 10^3 \) times smaller than the non-cooling estimate. Thus astrophysical scenarios for excess radio background proposed to explain the EDGES signal are comfortably ruled out.

Key words: galaxies: high-redshift – intergalactic medium – dark ages, reionization, first stars – diffuse radiation – radiation mechanisms: non-thermal.

1 INTRODUCTION

Very recently the EDGES (Experiment to Detect the Global Epoch of Reionization Signature) experiment has detected a broad \( (\Delta \nu / \nu \approx 1/4) \) absorption feature in the residual (after subtracting the dominant Galactic synchrotron contribution) sky brightness temperature centered at \( \nu \approx 78 \text{ MHz} \) (Bowman et al. 2018). Interpreting this dip in the brightness temperature as 21-cm absorption by the diffuse neutral intergalactic medium (IGM) at \( z = 1.42 \text{ GHz/78 MHz} \) \( \sim 17 \), whose spin temperature is coupled to the gas temperature via the Wouthuysen-Field effect (Wouthuysen 1952; Field 1959; for a review see Pritchard & Loeb 2012), the absorption frequency range is consistent with the standard models for the reionization of the IGM. However, the amplitude of the absorption feature is at least a factor of two larger than predicted by such models.

The global (averaged over the whole sky) brightness temperature corresponding to the emission/absorption of 21-cm photons for a background radiation characterized by a brightness temperature \( T_{bg} = T_R + T_{CMB} \); \( T_R \) and \( T_{CMB} \) are the brightness temperatures of a diffuse radio background and the CMB) at the redshift of absorption \( z \) is given by (see Eq. 1 in Barkana 2018)

\[
T_{21} = 36x_{HI}\left( \frac{\Omega_b h}{0.0327} \right)\left( \frac{\Omega_m}{0.307} \right)^{-1/2}\left( \frac{1 + z}{18} \right)^{1/2}\left( 1 - \frac{T_{bg}}{T_S} \right)
\]

in mK, where \( x_{HI} \) is the mass fraction of neutral hydrogen, \( \Omega_b \) and \( \Omega_m \) are the cosmic mean densities of baryons and matter respectively, \( h \) is the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}, and \( T_S \) is the spin temperature characterizing the level populations of the two hyperfine transition states. The...
spin temperature is expected to lie between the gas kinetic temperature ($T_K$) and the background radiation temperature ($T_{bg}$).

In the standard IGM evolution scenario all the background radiation at the relevant frequencies is due to the CMB. The CMB temperature at the relevant redshift is

$$T_{CMB} \approx 49 \left( \frac{1+z}{18} \right) \text{K}$$

and the lowest possible gas kinetic temperature in the standard scenario is 7 K (as mentioned in Barkana 2018). Thus the minimum brightness temperature for the absorption trough at 78 MHz, according to Eq. 1, is -216 mK. The brightness temperature measured by EDGES is $-500^{+200}_{-500}$ mK (errors correspond to 99% $\sigma$ confidence intervals; Bowman et al. 2018). Thus, even the maximum value of the observationally inferred $T_{21}$ (-300 mK) is lower than the minimum according to the standard scenario (-216 mK). From Eq. 1, the only way to lower $T_{21}$ is to either raise $T_{bg}$ (e.g., see Ewall-Wice et al. 2018; Mirocha & Furlanetto 2018; Fraser et al. 2018; Pospelov et al. 2018) or to lower $T_S$ (Barkana 2018).

The spin temperature can be lowered if the IGM can exchange energy with dark matter (DM). Compared to the IGM gas, DM (with a much smaller interaction cross-section compared to baryons) decoupled thermally from the CMB at a higher redshift and is expected to be cooler than gas due to adiabatic losses. Thus, the IGM can be cooled if the gas is thermally coupled to DM (Barkana 2018). However, this option severely constrains the DM properties, with much of the parameter space of viable DM candidates being ruled out from CMB observations, stellar cooling limits, etc. (Muñoz & Loeb 2018; Barkana et al. 2018; Berlin et al. 2018). Also, only a small subcomponent ($\sim 1\%$ by mass) of DM can be accommodated to explain the EDGES signal.

An alternative way to enhance the absorption signal is to raise the radio background ($T_{bg}$ in Eq. 1) at 21-cm in the rest frame of the absorbing IGM. The presence of an additional radio background (characterized by brightness temperature $T_R$) will increase the 21-cm absorption signal by an enhancement factor of

$$E = \frac{T_R/T_{CMB}}{1 - T_S/T_{CMB}} + 1 \approx \frac{T_R}{T_{CMB}} + 1,$$

since $T_S/T_{CMB} \approx T_K/T_{CMB} \sim 1/7 \ll 1$. Indeed there is an excess radio background measured at frequencies below 10 GHz, most recently highlighted by the ARCADE 2 experiment (Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission; Fixsen et al. 2011; see the recent conference summary on this by Singal et al. 2018). While this excess radio background cannot be accounted for by extragalactic radio point sources, most of it may be of Galactic origin (Subrahmanyan & Cowsik 2013). The brightness temperature of the excess radio background measured at 78 MHz is $\sim 600$ K (see Fig. 1 in Singal et al. 2018). We can explain the excess EDGES absorption if only a few K of this (comparable to the CMB brightness temperature at $z = 0$; see Eq. 3) is contributed by processes happening earlier than $z \sim 17$ (Feng & Holder 2018).

Astrophysical sources such as accreting supermassive black holes (SMBHs; Biermann et al. 2014; Ewall-Wice et al. 2018) and supernovae (SN) from the first stars (Mirocha & Furlanetto 2018) at $z \gtrsim 17$ can give the required excess radio background. This option, however, requires these sources to be $\approx 3$ orders of magnitude more efficient radio emitters compared to their low redshift counterparts. Another possible way to create the required excess radio background is through the production of photons in the Rayleigh-Jeans tail of the CMB via exotic models (e.g., Fraser et al. 2018; Pospelov et al. 2018).

In this Letter we show that the astrophysical mechanisms that require synchrotron emission from relativistic electrons to enhance the radio background at $z \approx 17$ are severely constrained because the cooling time (due to inverse-Compton and synchrotron losses) of these electrons is at least three orders of magnitude shorter than the duration of the EDGES absorption trough. This implies that the models that do not explicitly account for cooling of non-thermal electrons grossly overestimate the radio synchrotron background. Even in the absence of cooling losses the radio emissivity of the astrophysical sources have to be enhanced by $\sim 10^3$ to produce the required radio background, with cooling losses this factor becomes impossible high $\sim 10^6$! Although the importance of IC cooling and its contribution to X-ray background at high redshifts is acknowledged (e.g., see Oh 2001; Ghisellini et al. 2014), here we focus on the cooling argument in the context of the recent EDGES result.

Unless stated otherwise, all quantities in this Letter are expressed in physical (rather than comoving) units in the rest frame of the absorbing gas.

2 SYNCHROTRON RADIO BACKGROUND

In astrophysical scenarios, involving both SMBHs and SN, the excess radio background is produced by incoherent synchrotron emission due to relativistic electrons gyrating in magnetic field lines. In this Letter we do not calculate the radio brightness temperature ($T_R$) associated with SMBHs and star formation prior to $z \approx 17$, which depends on the detailed redshift and spectral variation of radio emission from these sources (e.g., see Eqs. 4, 5 in Ewall-Wice et al. 2018; Eq. 5 in Mirocha & Furlanetto 2018). Here we only mention that both these scenarios require $\sim 10^3$ enhancement of emission in the radio band compared to their low-redshift counterparts (Ewall-Wice et al. 2018; Mirocha & Furlanetto 2018).

The synchrotron emission at a frequency $\nu$ is related to the cyclotron frequency ($\nu_{cyc} = eB/2\pi mc$; $e$ is the charge of an electron, $B$ is magnetic field strength, $m_e$ is electron mass and $c$ is the universal speed of light) by $\nu \sim \gamma^2 \nu_{cyc}$, where $\gamma$ is the Lorentz factor of electrons with an isotropic momentum distribution. The Lorentz factor of electrons responsible for synchrotron emission at a frequency $\nu = 1.42$ GHz is given by

$$\gamma_{syn} \sim 730 \left( \frac{B}{10^{-3}\text{G}} \right)^{-1/2}.$$

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The magnetic field strength in our equations refers to the regions in which electrons are accelerated and confined to produce the excess radio background, and not to the strength of a global diffuse magnetic field. The synchrotron photons from a number of such sources is expected to result in an almost uniform large-scale radio background that may explain the global 21-cm absorption amplitude.

2.1 Synchrotron cooling time

The synchrotron cooling time \( t_{\text{syn}} \sim \gamma m_e c^2/\gamma^2 u_B \sigma_T c \) (\( u_B \equiv B^2/8\pi \) is magnetic energy density and \( \sigma_T \) is the Thomson scattering cross-section). Expressed in terms of \( B \),

\[
t_{\text{syn}} \sim 0.05 \text{Myr} \left( \frac{B}{10^{-3} \text{G}} \right)^{-3/2}.
\]

3 INVERSE-COMPTON CONSIDERATIONS

Typically, the relativistic electrons producing synchrotron emission in radio also emit at much higher frequencies due to the Compton upscattering of the background radiation (in our case dominated by the CMB).

3.1 IC cooling time

The IC cooling time for relativistic electrons is \( t_{\text{IC}} = \gamma m_e c^2/\gamma^2 u_B \sigma_c \) (\( u_B \) is the energy density of the background photons). The ratio of the IC cooling time to the synchrotron cooling time for the electrons producing the excess radio background is

\[
\frac{t_{\text{IC}}}{t_{\text{syn}}} \sim \frac{u_B}{u_B} \sim 0.91 \left( \frac{B}{10^{-3} \text{G}} \right)^2 \left( \frac{1 + z}{18} \right)^{-4},
\]

where we have assumed \( u_B = u_{\text{CMB}} = aT^4_{\text{CMB}} \) (a is the radiation constant). Thus the IC cooling time for these electrons (combining Eq. 6 with Eq. 5) is

\[
t_{\text{IC}} \sim 0.046 \text{Myr} \left( \frac{B}{10^{-3} \text{G}} \right)^{1/2} \left( \frac{1 + z}{18} \right)^{-4}.
\]

Figure 1 shows the synchrotron and IC cooling timescales as a function of the magnetic field strength at \( z = 17 \) and \( z = 0 \). Note that at \( z = 0 \) the IC and synchrotron cooling times cross at the field strength of \( B \approx 3 \) \( \mu \text{G} \). The same crossover at \( z = 17 \) occurs at \( B \approx 10^{-3} \) \( \text{G} \). Also note that the maximum value of the cooling time \( t_{\text{cool}} \approx \min\{t_{\text{syn}}, t_{\text{IC}}\} \); see Eq. 14) at \( z = 17 \) is about four orders of magnitude shorter than at \( z = 0 \), implying that the cooling losses are much more important at higher redshifts than now.

3.2 Soft X-ray background

Let us assume that synchrotron radio emission indeed produces the requisite radio background at \( z \sim 17 \). The same electrons are expected to upscatter the CMB photons and produce a uniform background at a frequency

\[
\nu_{\text{IC}} \sim \frac{\gamma_{\text{syn}}}{\gamma_{\text{syn}}} u_{\text{CMB}} \sim 1.5 \times 10^{18} \text{Hz} \left( \frac{B}{10^{-3} \text{G}} \right)^{-1} \left( \frac{1 + z}{18} \right)^4,
\]

which corresponds to 6.4 keV for the fiducial parameters. This IC background will be redshifted to soft X-rays (\( \sim 0.36 \) keV, or equivalently \( \nu \sim 8 \times 10^{16} \) Hz) at \( z = 0 \).

The synchrotron emissivity of relativistic electrons is given by

\[
\epsilon_{\nu,\text{syn}} \sim \gamma^2_{\text{syn}} u_B \sigma_T c \left[ \frac{d\nu}{d\gamma} \right]_{\nu \sim \nu_{\gamma,\text{syn}}} \gamma_{\text{syn}}^{-4},
\]

where \( d\nu/d\gamma \propto \gamma^{-p} \) is a power-law distribution of relativistic electrons. The IC emissivity produced by the upscattering of the CMB by the same electrons is related to it by \( \epsilon_{\nu,\text{IC}}/\epsilon_{\nu,\text{syn}} \sim u_{\text{CMB}} u_{\gamma,\text{syn}}/u_{\gamma,\text{IC}} \); a consequence of \( \nu_{\gamma,\text{IC}} \sim \gamma^2_{\text{syn}}/\nu_{\gamma,\text{CMB}} \). Therefore the ratio of IC and synchrotron emissivities per logarithmic interval in frequency is given by

\[
\frac{(\nu_{\gamma,\text{IC}})}{(\nu_{\gamma,\text{syn}})} \sim u_{\text{CMB}} / u_B \sim 1.1 \left( \frac{B}{10^{-3} \text{G}} \right)^{-2} \left( \frac{1 + z}{18} \right)^4.
\]

Figure 1. Important timescales for the relativistic electrons producing the excess radio synchrotron background as a function of the magnetic field strength: the duration of the EDGES signal (\( \Delta t_{\text{EDGES}} \); Eq. 12), the synchrotron cooling time (\( t_{\text{syn}} \); Eq. 5), the IC cooling time (\( t_{\text{IC}} \) at \( z = 0 \); 17; Eq. 7), and the cooling time \( t_{\text{cool}} \) (Eq. 14) at \( z = 17 \). The relativistic electrons will cool at the shorter of the synchrotron and IC cooling timescales, which at \( z = 17 \) is at least \( \sim 10^3 \) shorter than the duration of the EDGES absorption for all \( B \). Magnetic field strength lower than \( \sim 10^{-4} \) G (indicated by the blue shaded region) is ruled out from the soft X-ray background constraint (see section 3.2).
The age of the Universe at the redshift of the EDGES absorption trough \((z \approx 17)\), assuming a flat, matter-only Universe (a good assumption at those redshifts), is

\[
t_{age} \approx 180\text{Myr} \left(\frac{1+z}{18}\right)^{-3/2}.
\]

The EDGES absorption trough is centered at \(z \approx 17\) and has a duration \(\Delta z/z \approx 1/4\). For a flat matter-only Universe \(\Delta t/t = -3\Delta z/2(1+z)\), and therefore the time duration corresponding to the EDGES signal is

\[
\Delta t_{\text{EDGES}} = \frac{3}{2} t_{age} \frac{\Delta z}{1+z} \approx 67.5 \text{ Myr} \left(\frac{1+z}{18}\right)^{-3/2} \frac{\Delta z}{1/4}.
\]

Now if an enhanced radio background has to explain the EDGES absorption amplitude, it must be present for at least the duration of \(\Delta t_{\text{EDGES}}\). If the relativistic electrons are accelerated only at the beginning of the absorption feature at \(z \approx 20\) but are not replenished, they will cool off in \(\lesssim 0.025\) Myr (see Fig. 1) and therefore the required radio background cannot be sustained for \(\Delta t_{\text{EDGES}}\). This implies that we need continuous injection of relativistic electrons to replenish the cooling electrons. But even with the continuous injection of electrons, cooling is expected to steepen the radio spectrum at the relevant frequencies.

A one-zone model for the evolution of the relativistic electron density \(n_\gamma \equiv dn/d\gamma\) is given by (e.g., see Eq. 14 in Oh 2001)

\[
\frac{\partial n_\gamma}{\partial t} + \frac{\partial}{\partial \gamma}(\dot{\gamma} n_\gamma) = S_\gamma - \frac{n_\gamma}{t_{\text{esc}}},
\]

where \(\dot{\gamma} = \gamma/t_{\text{cool}}\),

\[
t_{\text{cool}} = \frac{1}{t_{\text{syn}} + t_{\text{IC}} + t_{\text{ad}}},
\]

is the cooling time due to synchrotron, IC and adiabatic cooling, \(S_\gamma\) is the source term for relativistic electrons, and \(t_{\text{esc}}\) is the escape timescale of relativistic electrons. In this Letter we ignore adiabatic losses and escape of electrons (including these will only strengthen our argument). The spectral index \(\alpha_\nu \equiv d\ln F_\nu/d\ln \nu\) and the electron power-law index \((p; n_\gamma \propto \gamma^{-p})\) are related as \(\alpha_\nu = -(p-1)/2\) (e.g., see Rybicki & Lightman 1986).

It is useful to recall the solution of Eq. 13 in some special cases (see Sarazin 1999 for a comprehensive treatment). If there is no injection \((i.e., S_\gamma = 0)\) but only cooling of an initial population of relativistic electrons, a cooling break occurs at \(\gamma\) (the corresponding \(\nu = \gamma^2 t_{\text{esc}}\) for which the cooling time equals the age of electrons; there are no electrons with a higher \(\gamma\) (the SED for this case is shown by the green dot-dashed line in Fig. 2). With constant injection, the electron index \(p\) steepens by 1 and the spectral index \(\alpha_\nu\) steepens by 0.5 beyond the cooling break (orange solid line in Fig. 2).

Extrapolating from \(z \approx 0\), Ewall-Wice et al. (2018) and Mirocha & Furlanetto (2018) use a shallow spectral index \((\alpha_\nu = -0.6, -0.7\) respectively\) for the radio emission from their \(z \approx 17\) sources. The corresponding electron indices are \(p = 2.2, 2.4\), consistent with the diffusive shock acceleration picture. These works do not account for cooling losses of the relativistic electrons which are clearly very important at \(z \approx 17\) as compared to \(z \approx 0\) (see Fig. 1).

The blue dashed line in Figure 2 shows the SED assumed by Ewall-Wice et al. (2018) and the orange solid line shows the same SED with cooling \((\text{assuming } B = 10^{-3} \text{ G corresponding to the longest } t_{\text{cool}} \approx t_{\text{syn}}/2 \approx t_{\text{IC}}/2 \approx 0.025 \text{ Myr}; \text{ see Fig. 1})\) and a source function \(S_\nu \propto \nu^{-2.5}\) (or equivalently \(S_\nu \propto \nu^{-0.8}\)) after a duration of \(0.025 \times 730 \approx 18.25\) Myr.

Figure 2. The average spectral energy distribution (SED) of the radio synchrotron sources under different scenarios of electron cooling after 18.25 Myr \((< \Delta t_{\text{EDGES}})\), corresponding to the cooling time of \(\gamma = 1\) electrons: (i) no cooling; (ii) continuous injection of electrons with cooling; and (iii) only cooling (and no continuous injection) of the initially relativistic electrons. For (ii) the spectral index \((d\ln F_\nu/d\ln \nu)\) becomes steeper by 0.5 beyond the cooling break; for (iii) there is no emission at frequencies higher than the cooling break. Since the minimum value of \(\Delta t_{\text{EDGES}}/t_{\text{cool}} > 10^3\) for all field strengths (see Fig. 1), the cooling break occurs at a very low frequency, and the flux at 1.42 GHz for (ii) is \(\approx 10^5\) lower than in absence of cooling (i).
(< Δ_{\text{EDGES}} = 67.5 \text{ Myr}; \text{ Eq. 12}), the time at which the cooling break for electrons reaches γ = 1 (ν = ν_{\text{cyc}} \approx 2500 \text{ Hz}).^{1} The cooling time for non-relativistic electrons emitting cyclotron photons becomes independent of energy and \( t_{\text{cool}} \propto \gamma^{-1} \) scaling breaks down, but the SED at Δt_{\text{EDGES}} will definitely be below the orange solid line in Figure 2. Thus reading off the values at 1.42 GHz for the orange and blue lines in Figure 2, we conclude that ignoring cooling losses overestimates the radio synchrotron flux by \( \gtrsim 10^3 \). Therefore, a robust conclusion is that the models in absence of cooling that need to be boosted by \( \sim 10^3 \) will need a further increase of \( \sim 10^3 \) to produce the required radio synchrotron background. This strong constraint essentially rules out synchrotron radio background as a solution to the enhanced 21-cm absorption seen by EDGES.

5 CONCLUSIONS

We conclude that astrophysical particle accelerators (first stars and supermassive black holes), with reasonable extrapolation from \( z \sim 0 \), cannot produce the radio synchrotron background at 1.42 GHz comparable to the CMB brightness temperature. Such a radio background is invoked by some models (e.g., Ewall-Wice et al. 2018; Mirocha & Furlanetto 2018) to explain the excess 21-cm absorption signature claimed by the EDGES experiment. The principal difficulty is that the cooling time (shorter of the synchrotron and inverse-Compton cooling times) of the relevant relativistic electrons is at least three orders of magnitude shorter than the duration of the EDGES signal. To get the required radio background, various astrophysical scenarios have to enhance the radio emissivity by \( \sim 10^3 \) compared to the \( z \sim 0 \) models. In the presence of non-thermal cooling losses considered in this Letter the required enhancement is expected to be \( \gtrsim 10^6 \), which seems almost impossible. Of course, there is the additional constraint from the soft X-ray background.

We note that the constraints in this Letter do not apply to scenarios in which the excess radio background is not produced by relativistic electrons (e.g., Fraser et al. 2018; Pospelov et al. 2018). With stringent constraints on dark matter cooling (Muñoz & Loeb 2018; Barkana et al. 2018; Berlin et al. 2018) and on astrophysical models based on excess radio background, it is imperative that the EDGES signal be confirmed with other experiments. Thankfully there are several such ongoing experiments (e.g., see Bernardi et al. 2016; Voytek et al. 2014; Singh et al. 2017).

We end by noting that the arguments in this Letter can be used to put tight constraints on the background radiation at high redshifts, independent of the fate of the EDGES signal.

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1 Synchrotron self absorption will become important at such low frequencies but the SED at 1.42 GHz (in the optically thin regime) will be unaffected.