Cosmology with the 21 cm line

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Abstract: The 21 cm line corresponds to an excited state of the neutral hydrogen. Therefore observations of that cosmologically redshifted line can unveil how the intergalactic gas became reionized at some redshift higher than 6. The absorption 21 cm line has been recently detected for the first time. However, its profile is highly unexpected as it implies a gas temperature lower than what is expected by all current cosmological models. In this contribution, the possibility that such a discrepancy arises from the fact that the observed 21 cm line was emitted from a typical low-density region is analysed. This has allowed us to substantially reduce the gas temperature discrepancy, which alleviates but not fully solves the problem.

I. INTRODUCTION

Reionization is a key factor in the study of galaxy formation and evolution. Matter became essentially neutral after recombination, occurred at redshift z~1100. However, the intergalactic media is nowadays fully ionized. It is believed that light sources, mainly active galactic nuclei, faint galaxies and first-generation Population III stars, reionized the cosmic gas at redshifts between 6 and 30. Such a reionization and the related photo-heating acted as negative feedback in the subsequent formation of galaxies. Consequently, galaxy formation and reionization are two intertwined processes, which play a crucial role in modern cosmology [1]. Yet, they are still poorly determined.

Most investigations on reionization try to uncover when it took place. Those studies are based on the anisotropy of the cosmic microwave background (CMB) radiation and the spectra of distant light sources, obtaining that the epoch of reionization (EoR) ended at z~6. Nevertheless, we still do not know how it proceeded.

A possible source of information that would solve that issue is provided by 21 cm line observations. Neutral hydrogen has an excited state of hyperfine structure causing a spectral line at 21 cm [2]. Therefore, neutral hydrogen is seen in absorption or emission over the CMB, depending on whether the spin temperature, T_S, is lower or higher than the CMB temperature, respectively.

Using the redshifted 21 cm line we could map the hydrogen neutral fraction in the past. Therefore, we could obtain the evolution of the neutral gas over time, and consequently, we could have crucial information about the EoR.

Unfortunately, the results recently obtained in the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) on the 21 cm line are astonishing. The absorption profile detected in the sky-averaged radio spectrum shows an important discrepancy with the expected temperature of the neutral gas at high redshift.

In this contribution I present the issue arising from EDGES' observations, and discuss its implications. I report the possible different solutions proposed by the scientific community to the problem. Finally, I analyse one very simple possible solution to the problem, which has so far not been considered.

II. EDGES

As mentioned, the observations of the 21 cm line are crucial for the study of reionization. Nonetheless, these observations are hard to perform. The order of magnitude of the 21 cm signal is really small (10^{-5} the contribution from the neutral hydrogen inside galaxies), so it is difficult to detect with current instrumentation. Besides, the 21 cm line relies mainly on the evolution of intergalactic gas which is heated by galaxies. Hence, to obtain detailed information on the 21 cm line we must have an accurate modelling of the evolution galaxies and intergalactic gas. However, one recent experiment has apparently detected for the first time the 21 cm line.

In August 2015 the Experiment to Detect the Global EoR Signature (EDGES) started its observations. EDGES uses two low-band instruments that consist of a single-polarisation dipole antenna able to detect radio spectra at low magnitudes. The absorption profile is found by fitting the integrated spectrum with the foreground model and a model for the 21-cm signal simultaneously. The best-fitting 21-cm model has a U-shaped absorption profile centred at 78 MHz with a full width at half maximum of 19 MHz and amplitude of 0.5 K. This absorption profile is centred at $z \sim 17$ and spans approximately 20>z>15 (see Figure 1) [3].

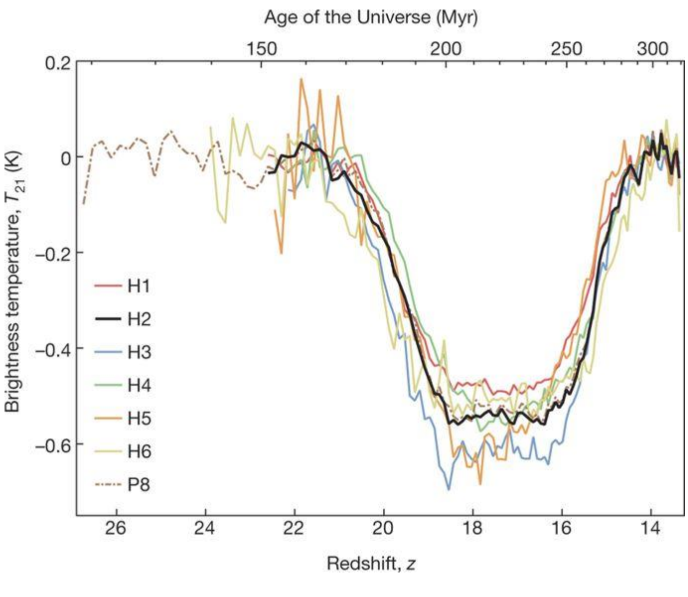

FIG. 1: Brightness temperature as a function of the redshift obtained by the EDGES observations. We see a drop in

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brightness temperature at $z \sim 20$ and the recovery of the normal value at $z \sim 15$.

The brightness temperature δT of the 21 cm signal is mainly given by the temperature difference between the CMB radiation temperature, $T_R(z)$, and hydrogen neutral gas spin temperature, $T_S(z)$, through the expression [4]

$$\delta T \approx 0.14 \text{ K} \times x_{HI}(z)\Omega_b h\left(\frac{1+z}{\Omega_m}\right)^{1/2}\left[1-\frac{T_R(z)}{T_S(z)}\right] \qquad (1)$$

where x_{HI} is the hydrogen neutral fraction, Ω_m and Ω_b are the matter and baryon density parameters, i.e. their corresponding densities normalized to the critical density, and h is the Hubble constant relative to 100 Km/(s Mpc). This allows one to estimate $x_{HI}(z)$ by measuring $T_S(z)$, since $T_R(z)$ is known from the CMB temperature. In the present case, we will assume the most favourable case that T_S equals the neutral gas temperature, T_G, i.e. we will assume that the gas has not been heated by stars yet.

A. Problematic implications

The background radiation and gas keep coupled in the early Universe through Compton scattering, so both components have the same temperature: $T_R = T_G$. At approximately $z \sim 150$ the gas density is not enough to keep the Compton scattering [5] [6], and the gas and background radiation decouple. Then the gas approximately cools adiabatically as, $T(z)\alpha\ (1+z)^2$, while radiation temperature cools more slowly as $T_R(z)\alpha\ (1+z)$.

The signal δT detected by EDGES (see Figure 1) implies a ratio $T_R/\ T_S = T_R/\ T_G$ equal to 15 at $z = 17$ (equation (1)). However, the previous temperature dependences predicted in the standard cosmology imply that at $z \sim 17$ the radiation temperature is 49.05 K and the gas temperature is 7 K, so the theoretical ratio is rather $T_R/\ T_S = 7$. In order words, the ratio $T_R/\ T_S$ implied by observations is more than a factor of two greater than the theoretical ratio [7].

To justify the observations, at $z \sim 17$, for a gas temperature equal to the theoretical gas temperature (7K), T_R should be larger than 105 K instead of 49.05 K. Conversely, for a radiation temperature equal to the theoretical value (49.05 K), T_G should be lower than 3.27 K instead of 7 K.

This result causes a great puzzle to the scientific community. Either the signal is fake, or current cosmological models of the CMB or the intergalactic gas evolution are wrong. It is believed that the problem comes from the gas temperature, since there is more information and verified data on the CMB radiation temperature.

B. Possible solutions

To validate the 21 cm line signal obtained numerous hardware and processing tests were performed. There are also no known alternatives that can account for the observed profile. The scientific community has proposed different solutions for the conflict, but none of them could be verified, and they all question the settled knowledge.

One possible way to solve the problem is to assume that the gas is actually at a lower temperature than what it is expected current from models. This could be the case if the gas and CMB radiation decouple at a z larger than the currently expected one, $z{\sim}150$, so that the gas would cool adiabatically earlier. In order to fit the temperature obtained from the amplitude of the 21 cm line, gas should decouple by z~250. This could be caused by a fraction of residual electrons lower than expected, leading to an early decoupling [3]. However, this solution is not accepted, because the residual ionization fraction is determined by different sources with little uncertainty.

There are other rarer possible solutions, which are mainly related to dark matter. Existing models of dark matter do not affect the gas and CMB temperatures. Nevertheless, it could be that the existence of dark matter induces mechanisms such as synchrotron emissions, related to primordial black holes [8] or relativistic electrons from metastable particles [9], which could increase the background radiation temperature.

Another possible solution related to the existence of dark matter is the cooling of the gas as a result of interactions with axions [10]. Axion is a hypothetical elementary particle which could somewhat interact at those z with ordinary gas. Axions would be at a lower temperature than the gas, so the gas temperature could slightly decrease provided that axions and gas particles slightly interact.

III. ONE POSSIBLE SIMPLER EXPLANATION

Another simpler explanation for finding a gas temperature lower than expected could be that the neutral hydrogen of the 21 cm line actually lies in low-density regions, since upper density regions collapsed and formed stars that reionized the gas around them. Therefore, the 21 cm line would be emitted from low-density regions, whose temperature is lower than the global mean temperature of the gas.

As mentioned, the gas and the radiation are coupled in the early Universe through Compton scattering. In regions with lower density, the Compton scattering stops working earlier and corresponding temperatures T_R and T_G begin to evolve as $T_R(z)\alpha\ (1+z)$ and $T_G(z)\alpha\ (1+z)^2$. That means that an earlier decoupling would cause the gas temperature to be lower at $z \sim 17$. Gas density decreases with redshift as $\rho(z)\alpha\ (1+z)^3$. The gas with the mean cosmic density decouples at $z = 150$, but low-density regions, decouple sooner.

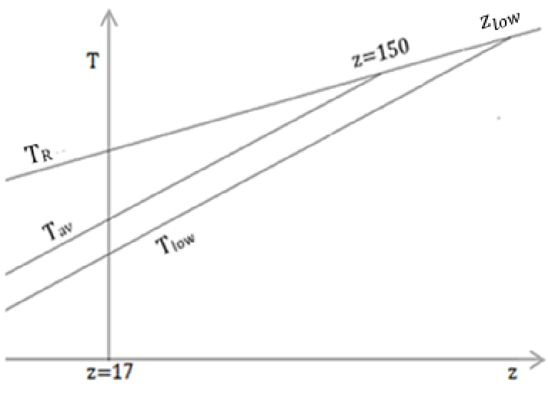

FIG. 2: Evolution of the gas temperature with redshift in a region with the mean cosmic density $\bar{\rho}$ and another region with a lower density ρ_{low}. T_R is the temperature of the background radiation and follows $T_R(z)\alpha\ (1+z)$. T_{low} is the

temperature of the low-density gas region and T_{av} is the temperature of the region with $\bar{\rho}$, both satisfying $T(z) \alpha (1+z)^2$.

According to Figure 2, knowing that a region with average density $\bar{\rho}$ and average temperature T_{av} decouples at $z = 150$, we can readily determine the redshift of decoupling, z_d, of a region with lower density ρ_{low} and corresponding temperature T_{low}.

IV. TEMPERATURE OF TYPICAL LOW-DENSITY REGIONS

A. Typical low-density region

The density, ρ_{low}, of the typical low-density neutral region at $z = 17$ emitting the 21 cm signal can be obtained from the typical density fluctuation of the suited mass scale, defined as $\sigma = \langle(\rho - \bar{\rho}/\bar{\rho})^2\rangle^{1/2}$, where $\bar{\rho}$ is the mean cosmic density at the redshift.

The typical density fluctuation on a length scale R or mass scale $M_h = \frac{4}{3}\pi R^3 \bar{\rho}$ at $z = 17$ can in turn be calculated from the well-known typical density fluctuation on scale $R = 8\,Mpc$ at $z = 0$.

The mass scale of the typical low-density neutral region is approximately equal to the minimum mass of haloes that form stars at $z = 17$, M_h, provided by simulations of galaxy formation. Indeed, negative fluctuations of that mass scale are the most common ones, and are embedded in other low-density regions of larger scales.

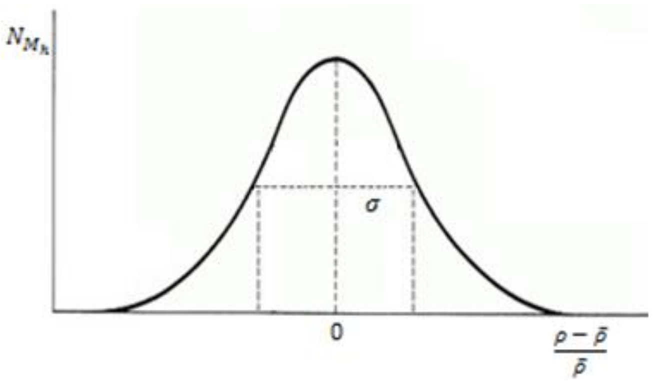

FIG. 3: Gaussian distribution of density fluctuation, $(\rho - \bar{\rho})/\bar{\rho}$, at a given mass scale M_h, and σ is the typical density fluctuation.

As shown in Figure 3, fluctuations of a given contrast $(\rho - \bar{\rho})/\bar{\rho}$ are Gaussian distributed, which is a well-known property of density fluctuations in our Universe. To facilitate the calculations we can assume that all positive fluctuations of the mass scale, M_h, have collapsed in haloes. Collapsed haloes would result in ionized regions, so that they do not contribute to the 21 cm line. Therefore, the density of typical low-density neutral regions that contribute to the 21 cm line will be given by the typical negative fluctuation:

$$-\sigma = \frac{\rho_{low} - \bar{\rho}}{\bar{\rho}} \tag{2}$$

In order to obtain ρ_{low}, we must first derive the average density of the gas at $z = 17$. As we saw before, $\rho\ \alpha\ (1+z)^3$, thus:

$$\bar{\rho}(z=17) = \bar{\rho}(z=0)(1+17)^3 = 2{,}333 \times 10^{14}\, M_{\odot}/Mpc^3 \tag{3}$$

where $\bar{\rho}(z=0) = 4 \times 10^{10}\, M_{\odot}/Mpc^3$, is the current cosmic mean density of the universe.

We can obtain σ at the suited mass scale at z = 17. Its dependence over z is $\sigma\ \alpha\ 1/(1+z)$. Therefore knowing the present value $\sigma(z=0, R=8Mpc) = 0{,}831$, we can obtain:

$$\sigma(z=17, R=8Mpc) = \frac{\sigma(z=0)}{(1+17)} = 0{,}0462 \tag{4}$$

Its dependence on mass is $\alpha\, M^{-(\frac{n+3}{6})}$, where n=-2.15. Therefore knowing the mass corresponding to R = 8 Mpc at z=0, calculated by:

$$M(R=8Mpc) = \frac{4}{3}\pi R^3 \times \bar{\rho}(z=0) = 8{,}578 \times 10^{13} M_0 \tag{5}$$

we can obtain $\sigma(z=17, M_h)$. M_h is the minimum mass of the haloes that form stars at $z = 17$, its value is $5 \times 10^5 M_{\odot}$. So:

$$\sigma(z=17, M_h) = \sigma\begin{pmatrix} z=17, \\ R=8Mpc \end{pmatrix} \frac{M_h^{-\left(\frac{n+3}{6}\right)}}{M(R=8\,Mpc)^{-\left(\frac{n+3}{6}\right)}} = 0{,}678 \tag{6}$$

Given the typical density fluctuation on the wanted scale at z=17, we can obtain the density of the low-density region. Accordingly to equation (2), we obtain

$$\rho_{low} = \bar{\rho}(z=17) - \bar{\rho}(z=17)\sigma(z=17,\, M_h) = 7.51 \times 10^{13}\, M_{\odot}/Mpc^3 \tag{7}$$

B. Corresponding temperature

Detailed calculations provide a gas temperature of 7 K at $z = 17$ [7]. However, we will work assuming fully adiabatic evolution of the gas, since it decouples. Therefore, to have a temperature of 7 K at $z = 17$ in our calculations, we assume that gas decouples later, at z_d. To find the z_d which the gas with the mean cosmic density decouples, we can use the dependences over redshift $T(z) \alpha (1+z)^2$ and $T_{th}(z = 17) = 7\,K$. So:

$$(1+z_d)^2 = (1+17)^2 \frac{T_{th}(z_d)}{T_{th}(z=17)} \tag{8}$$

$$T_{th}(z_d) = T_R(z_d) = 2{,}725\,(1+z_d) \tag{9}$$

Taking into account equations (8) and (9), we arrive at:

$$z_d = (1+17)^2 \frac{2{,}725}{T_{obs}(z=17)} - 1 = 125 \qquad (10)$$

As mentioned, regions with average density decouple at $z = 150$. However, detailed calculation using all values provided in [7] and the effective dependence of temperature assuming fully adiabatic evolution since z_d, yields $z_d = 125$.

The next step is to know the redshift z_{low} of decoupling of the typical low-density region. The density of decoupling is obviously the same as the average density of decoupling of the whole universe at $z = 125$. Knowing its dependence over z, and equation (10):

$$(1+z_{low})^3 = \frac{\bar{\rho}(z=17)}{\rho_{low}(z=17)}(1+125)^3 \qquad (11)$$

The result is $z_{low} = 182.82$.

The temperature at decoupling of such a low-density region is thus:

$$T_{low}\,(z_{low}) = T_R(z_{low}) = 2{,}725\,(1+z_{low}) = 500.9\,K \qquad (12)$$

And the corresponding temperature at $z = 17$ is:

$$T_{low}(z=17) = T_{low}(z_{low})\frac{(1+17)^2}{(1+z_{low})^2} = 4.8\,K \qquad (13)$$

Therefore, we have obtained that the temperature $T_{low}$of the neutral gas in the typical low-density region is 4.8 K, which is 2.2 K lower than found for the average density region. We thus see that the theoretical neutral hydrogen temperature drops considerably. Nevertheless, the new temperature is not low enough to fully account for justify the discrepancy observed.

The result obtained here is, nonetheless, very encouraging, given the approximations made in the present calculations. Indeed, we have approximated the mass scale of the typical underdense region emitting the 21 cm line by the minimum mass of haloes that formed stars, and we have taken that density given by the negative typical density fluctuation. Hence, it could be that with more accurate calculations, the result could fully solve the discrepancy.

V. DENSITY AND MASS REQUIRED

To end up we are going to look for the density and mass scale $M_h$that would just fix the discrepancy, since these quantities are the main focus of our approximations.

To do that, we must perform the calculations in the opposite direction. Given the gas temperature obtained by the observations, $T_{obs}(z=17) = 3.27$, we can determine the redshift of decoupling z_{low}.

$$(1+z_{low})^2 = (1+17)^2 \frac{T_{obs}(z_{low})}{T_{obs}(z=17)} \qquad (14)$$

$$T_{obs}\,(z_{low}) = T_R(z_{low}) = 2{,}725\,(1+z_{low}) \qquad (15)$$

Taking into account equations (14) and (15), we arrive at:

$$z_{low} = (1+17)^2 \frac{2{,}725}{T_{obs}(z=17)} - 1 = 269 \qquad (16)$$

The next step is to find the density that would cause decoupling at $z_{low} = 269$. This is given by the relation:

$$\rho_{obs}(z=17) = \frac{\bar{\rho}(z=17)}{(1+z_{low})^3}\,(1+125)^3 = 2.371 \times 10^{13}\, M_{\odot}/Mpc^3 \qquad (17)$$

Given that density, we can obtain the corresponding typical density fluctuation σ_{low} at z=17:

$$\sigma_{low} = \left|\frac{\rho_{obs} - \bar{\rho}}{\bar{\rho}}\right| = 0.8984 \qquad (18)$$

Finally we obtain the typical mass of the halos that would be able to give that fluctuation of density:

$$M_h^{-\left(\frac{n+3}{6}\right)} = \sigma(M_h)\frac{M(R = 8\,Mpc)^{-\left(\frac{n+3}{6}\right)}}{\sigma(z=17)} \qquad (19)$$

The result is $M_h = 6.8 \times 10^4 M_{\odot}$.

Compared to the mass used in the previous calculations it is just only one order of magnitude lower.

Taking into account that the density and mass scale required to explain the discrepancy were approximate, the difference of one order of magnitude is quite reasonable.

VI. CONCLUSIONS

The 21 cm signal recently detected implies that either the radiation temperature is larger or the gas temperature lower than so far believed. Since there is little doubt on the radiation temperature, the problem is believed to arise from a wrong prediction of the gas temperature. Observations indicate that the gas temperature at $z = 17$ should be 3.27 K, which current cosmological models set this temperature to 7 K.

The theoretical temperature of 7 K mentioned above corresponds to a region with the mean cosmic density. However, the neutral hydrogen emitting the 21 cm line should lie in underdense regions, since high density regions collapsed and formed stars that reionized gas around them. As argued, that different density could be the origin of the different temperature detected.

We have calculated approximately the average temperature of a typical low-density neutral region, obtaining a temperature of 4.8 K. The temperature of the neutral region emitting the 21 cm signal so derived drops considerably; it is 2.2 K lower than so far estimated, which notably alleviates the problem. Nevertheless, the new theoretical temperature is not low enough to fully account for the discrepancy found.

The calculations performed involve some approximations that could affect the temperature derived. In particular, we have assumed that every positive density fluctuation on the scale of the minimum halo mass able to form stars collapses and is reionized, so that the typical low-density region emitting the 21 cm signal corresponds to the negative typical density fluctuation.

To check whether with more precise calculations the discrepancy would fully disappear, we have calculated the density and the mass scale that would lead to the observed temperature. The mass scale required is just one order of magnitude lower. This suggests that this explanation with more accurate calculations could solve the issue.

In conclusion, although the result obtained is not enough to fully solve the problem, the explanation proposed that the 21 cm line signal detected by EDGES was produced in one low-density neutral region, could be correct.

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