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Detailed Explanation of the Latest Puzzling Observation of the 21 cm Radio Line from the Early Universe: the Role of the Singular Kind of Hydrogen Atoms

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ABSTRACT: In our previous paper (Oks 2018) – referred below as paper I – we brought to the attention of the astrophysical community the existence of a "singular kind of hydrogen atoms" (hereafter, SKHA) and its possible role in explaining a puzzling observational results published in Nature by Bowman et al (2018a). The existence of the SKHA was proven in Oks paper (2001) both theoretically and by the analysis of atomic experiments. Bowman et al (2018a), observed the absorption profile of the redshifted 21 cm line from the early Universe. Bowman et al (2018a) observed the absorption profile of this line and found that the amplitude of the profile was more than a factor of two greater than the largest predictions. This could mean that the primordial *hydrogen gas was much cooler than expected*. In the present paper we provide more details – compared to paper I – on the alternative explanation of the puzzling observational results from Bowman et al paper (2018a). We show that the possible presence of the SKHA would lower the excitation temperature of the hyperfine doublet (the spin temperature) in two ways. First, by lowering the kinetic gas temperature to some effective value. Second, by lowering the color temperature of the radiation field in the Lyman series (responsible for the Wouthuysen-Field effect) to a much lower effective value. The combined effect of the SKHA seems to be sufficient for explaining the puzzling observational results by Bowman et al (2018).

***Kew words*:** singular kind of hydrogen atoms; explanation of the puzzle of 21 cm radio line; early Universe; cosmic microwave background; Wouthuysen-Field effect

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1. INTRODUCTION

In our previous paper (Oks 2018) – referred below as paper I – we brought to the attention of the astrophysical community the existence of a "singular kind of hydrogen atoms" (hereafter, SKHA) and its possible role in explaining a puzzling observational results published in Nature by Bowman et al (2018a). The existence of the SKHA was proven in Oks paper (2001) both theoretically and by the analysis of atomic experiments. Important details about the SKHA were briefly reiterated in paper I. The above word "singular" refers to the fact that the SKHA are described by the singular solution of the Dirac equation outside of the proton.[1/]

As for the puzzling result by Bowman et al (2018a), they observed the 21 cm line (redshifted from the rest frequency of 1,240 MHz to the frequency of 78 MHz) from the early Universe. Bowman et al (2018a) observed the absorption profile of this line: namely, as hydrogen atoms absorb photons from the cosmic microwave background (CMB). (The underlying physical mechanism was the ultraviolet light from stars formed in the early Universe – the light that is expected to penetrate the primordial hydrogen gas and to alter the excitation of the hydrogen 21 cm hyperfine structure line.) Bowman et al (2018a) found that the amplitude of the profile was more than a factor of two greater than the largest predictions. This could mean that the primordial *hydrogen gas was much cooler than expected*, as noted by Bowman et al (2018a).

[1/]Here and below, by "singular" we mean the strongly-singular solution of the Dirac equation for the Coulomb field – in distinction to the commonly accepted "regular" solution that has a weak singularity at the origin.

Hills et al (2018) expressed concerns about some aspects of the data processing by Bowman et al (2018a), though it was admitted by Hills et al (2018) that their analysis does not prove that the feature identified by Bowman et al. (2018a) is absent. In response, Bowman et al (2018b) pointed out that they conducted tests that showed that the recorded absorption signal was indeed astronomical (rather than having to do with the data processing). Bowman et al (2018b) also wrote that they have data that exclude some of the alternative signal models proposed by Hills et al (2018).

Several astrophysical explanations of the result by Bowman et al (2018a) were proposed in the literature. The first proposition was presented by Barkana (2018). He suggested that the additional cooling of the hydrogen gas was due to collisions with some kind of a dark matter. According to Barkana (2018), these dark-matter particle must be lighter than 4.3 GeV (meaning that they could have, e.g., the baryonic mass). Within the range of "lighter than 4.3 GeV" Barkana did not provide any specificity about the dark matter he resorted to.

Feng and Holder (2018) proposed that the results by Bowman et al (2018a) could be explained by a high-z radio background supplementing the cosmic microwave background (CMB) as the illuminating backdrop. Ewall-Wice et al (2018) suggested that the additional radio background could arise from accretion onto growing black holes.

For completeness we note that Barkana's suggestion (2018) was criticized by Mirosha and Furlanetto (2019). They wrote that a weakly charged dark matter particle (capable of cooling the baryons through Rutherford scattering) cannot account for the signal observed by Bowman et al (2018a) without causing tension elsewhere. For example, Muñoz & Loeb (2018) estimated that if there is a charged dark matter particle, it can only constitute ~ 10 per cent or less of all of the dark matter. Muñoz & Loeb (2018) suggested that the results by Bowman et al (2018a) could be explained if less than one per cent of the dark matter has a mini-charge, a million times smaller than the electron charge, and a mass in the range of 1–100 times the electron mass.

However, for fairness it should be clarified that Barkana (2018) himself wrote that the subcase of a weakly charged dark matter should be probably ruled out. Instead, Barkana (2018) assumed some kind of a non-standard Coulomb-like interaction between dark-matter particles and baryons that does not depend on whether the baryons are free or bound within atoms.[2/]

In the present paper we provide more details – compared to paper I – on the alternative explanation of the puzzling observational results from Bowman et al paper (2018a).

2. DETAILS ON THE ALTERNATIVE EXPLANATION OF THE PUZZLING OBSERVATION OF THE 21 CM RADIO LINE FROM THE EARLY UNIVERSE

The intensity of the observable 21 cm line from the early Universe is given as the brightness temperature T_B, which is a linear combination of the CMB temperature T_{CMB} and the spin temperature T_S (the latter being the excitation temperature of the hyperfine transition).

The standard expression for the spin temperature, as presented, e.g., in Field paper of year 1958 (see also, e.g., paper by Zaldarriaga et al (2014) and review by Furlanetto et al (2006)) is the following:

$$T_S = (T_{CMB} + y_c T_K + y_{Ly} T_{Ly})/(1 + y_c + y_{Ly}). \tag{1}$$

Here the 2nd term in the numerator relates to the collisional excitation of the hyperfine transition, which couples T_S to the gas kinetic temperature T_K, y_c being the corresponding coupling coefficient. The 3rd term in the numerator relates to the Wouthuysen-Field effect: T_{Ly} is the color temperature of the radiation field in the Lyman series and y_{Ly} is the corresponding coupling coefficient. Physically, the Wouthuysen-Field effect is the transition between the

2/Our paper should not be construed as a criticism of Barkana (2018) paper: we greatly appreciate his paper and use some numerical estimates from it.

hyperfine structure sublevels of the ground state facilitated by the absorption and the subsequent reemission of a photon of the Lyman series – mostly the Ly-alpha photon.

The coupling coefficients in Eq. (1) are as follows:

$$y_c = C_{10}T_*/(A_{10}T_K), \qquad y_{Ly} = P_{10}T_*/(A_{10}T_{Ly}). \tag{2}$$

Here $C_{10}(T_K)$ is the collisional de-excitation rate of the triplet hyperfine sublevel (labeled 1) to the singlet hyperfine sublevel (labeled 0), $T_* = 0.068$K, A_{10} is the corresponding Einstein coefficient, P_{10} is the direct de-excitation rate of the sublevel 1 due to absorption of an Lyá photon followed by the decay to sublevel 0.

Bowman et al (2018a) noted that the most intensive observed absorption signal corresponded to the redshift $z \approx 17$. Since the CMB temperature is $T_{CMB} = 2.725(1 + z)$ K, than at $z \approx 17$ there was $T_{CMB} \approx 49$ K. According to the standard cosmology, at $z \approx 17$ there was $T_K \approx 7$ K, as noted by Barkana (2018). However, for explaining the anomalous brightness of the absorption signal observed in 2018 by Bowman et al (while the spin temperature T_S is given by Eq. (1)) the gas kinetic temperature T_K should not exceed 5.1 K, as also noted by Barkana (2018).

Our alternative explanation of the puzzling observational result from Bowman et al paper (2018) is the following. Let us follow the logic of Barkana (20180 paper, but with the substitution of an unspecified dark matter by the SKHA.

In distinction to usual hydrogen atoms, the SKHA do not have excited discrete states that can be radiatively coupled to the ground state. (The SKHA still have two hyperfine sublevels of the ground state corresponding to the same 21 cm wavelength as usual hydrogen atoms.) This affects the spin temperature T_S in the following two ways.

First and foremost, the SKHA decouple from the CMB *earlier* than usual hydrogen atoms. Indeed, the SKHA decouple from the CMB when, in the course of the Universe expansion, the CMB temperature drops to the value $T_{CMB,S} = \alpha U_i$, where U_i is the ionization potential of all kinds of hydrogen atoms and α is a coefficient of the order $10^{-1.5}$ (whose exact value is immaterial for the present reasoning because it will cancel out); the additional superscript S of $T_{CMB,S}$ stands for SKHA. In distinction, the usual hydrogen atoms decouple from the CMB at $T_{CMB,U} = \alpha E_{21}$, where $E_{21} = 3U_i/4$ is the energy difference between the first excited and ground states; the additional superscript U of $T_{CMB,U}$ stands for usual hydrogen atoms. To visualize: as the CMB temperature drops from $T_{CMB,S}$ to $T_{CMB,U}$, the CMB can still radiatively couple numerous discrete excited states of usual hydrogen atoms to the ground state and then at $T_{CMB} < T_{CMB,U}$ there are no more excited states to be radiatively coupled to the ground state. For the AKHA already at $T_{CMB} < T_{CMB,S}$ there are no discrete excited states that can be radiatively coupled to the ground state. Obviously, $T_{CMB,U}/T_{CMB,S} = E_{21}/U_i = 3/4$.

Let us denote by a_1 the value of the expansion parameter a of the Universe at the AKHA decoupling from the CMB, i.e., at $T_{CMB,S}(a_1) = \alpha U_i$. Obviously, the kinetic gas temperature $T_{K,A}(a_1)$ of the SKHA at $a = a_1$ is equal to $T_{CMB,S}(a_1)$, so that $T_{K,S}(a_1) = \alpha U_i$.

Let us denote by a_2 the value of the expansion parameter of the Universe at the decoupling of usual hydrogen atoms from the CMB, i.e., at $T_{CMB,U}(a_2) = \alpha E_{21}$. Obviously, the kinetic gas temperature $T_{K,U}(a_2)$ of usual hydrogen atoms at $a = a_2$ is equal to $T_{CMB,S}(a_2)$, so that $T_{K,S}(a_2) = \alpha E_{21}$.

As the SKHA decouple from the CMB, their kinetic gas temperature $T_{K,A}$ evolves proportional to $1/a^2$ (assuming an adiabatic expansion for simplicity), so that $T_{K,S} = C/a^2$, where C is some coefficient. Therefore, $T_{K,S}(a_2)/T_{K,S}(a_1) = (a_1/a_2)^2$. As for the CMB temperature, it evolves proportional to 1/a, so that $T_{CMB}(a_2)/T_{CMB}(a_1) = a_1/a_2$. Consequently, by using relations $T_{K,S}(a_1) = T_{CMB}(a_1)$ and $T_{K,U}(a_2) = T_{CMB}(a_2)$, for the ratio $T_{K,S}(a_2)/T_{K,U}(a_2)$ one obtains:

$$T_{K,S}(a_2)/T_{K,U}(a_2)=T_{K,S}(a_2)/T_{CMB}(a_2)=[T_{K,S}(a_2)/T_{K,S}(a_1)][T_{CMB}(a_1)/T_{CMB}(a_2)]=(a_1/a_2)^2(a_2/a_1)= a_1/a_2. \tag{3}$$

Since $a_1/a_2 = T_{CMB}(a_2)/T_{CMB}(a_1) = E_{21}/U_i$, the final result for the above ratio is:

$$T_{K,S}(a_2)/T_{K,U}(a_2) = E_{21}/U_i = 3/4. \quad (4)$$

Thus, at $a = a_2$, the SKHA fluid is colder than the fluid of usual hydrogen atoms. At some $a > a_2$, the two fluids come to the thermal equilibrium with each other (due to the scattering of the usual hydrogen atoms with the SKHA), so that their effective (final) kinetic temperature is as follows

$$T_{K,eff} = (T_{K,U}n_U + T_{K,S}n_S)/(n_U + n_S) = (T_{K,U} + T_{K,S}n_S/n_U)/(1 + n_S/n_U) = \quad (5)$$

$$= T_{K,U}[1 + (3/4)\, n_S/n_U]/(1 + n_S/n_U) = T_{K,U}[1 + (3/4)\, (\rho_S/\rho_U)\mu_U/m_S]/[1 + (\rho_S/\rho_U)\mu_U/m_S],$$

where n_U and n_S are the corresponding number densities, ρ_U and ρ_S are the corresponding mass densities, μ_U is the mean molecular mass of the (usual) neutral primordial gas, m_A is the atomic hydrogen mass (m_A = 0.939 GeV). By using the same numerical values as employed by Barkana (2018) (see, e.g., Eq. (3) from his paper), Eq. (5) can be represented in the form:

$$T_{K,eff} \approx T_{K,U}[1 + (3/4)(6\ \mathrm{GeV})/m_S]/\ [1 + (6\ \mathrm{GeV})/m_S] \approx 0.79\ T_{K,U}. \quad (6)$$

Consequently, with the allowance for possible SKHA, at the redshift $z \approx 17$, the effective kinetic gas temperature would be lower than the lowest possible kinetic gas temperature $T_{K,U} \approx 7$ K in the standard scenario. Namely, it would be $T_{K,eff} \approx 0.79\ T_{K,U} \approx 5.5$ K. This temperature is much closer to the threshold estimated as ≈ 5.1 K (required for explaining the observations by Bowman et al (2018) in the standard scenario), than $T_{K,U} \approx 7$ K. In detail, while $T_{K,U} \approx 7$ K exceeded 5.1 K by more than 37%, the effective temperature $T_{K,eff} \approx 5.5$ K exceeds 5.1 K only by less than 8%, which it within the error margin of the estimated value of $T_{K,eff}$.

Moreover, this significant improvement is just one way, in which the possible SKHA affect the spin temperature T_S: by lowering the kinetic gas temperature T_K entering Eq. (1). Simultaneously, the possible SKHA lowers T_S also in another way, as follows.

The SKHA are not subjected to the Wouthuysen-Field effect because they do not have states required for the absorption or emission of Lyman quanta – in distinction to the usual hydrogen. Therefore, for the corresponding mixture of usual hydrogen atoms and the SKLA, Eq. (1) for the spin temperature should be modified as follows:

$$T_S = [T_{CMB} + y_c T_{K,eff} + y_{Ly} T_{Ly}(\rho_U/\rho_S)m_S/\mu_U]/[1 + y_c + y_{Ly}(\rho_U/\rho_S)m_S/\mu_U] \approx \quad (7)$$

$$\approx [T_{CMB} + y_c(0.79T_{K,U}) + y_{Ly}(0.16T_{Ly})]/(1 + y_c + 0.16y_{Ly}).$$

The combined effect of the SKHA, i.e., the lowering of the kinetic gas temperature to the effective value of $0.79T_{K,U}$ and the lowering of the color temperature of the radiation field in the Lyman series to the effective value of $0.16T_{Ly}$, seems to be sufficient for explaining the observations by Bowman et al (2018a).

3. CONCLUSIONS

In the present paper we explored a "what if" scenario: what if in place of some unspecified dark matter resorted to by Barkana (2018) for explaining the observations by Bowman et al (2018a), one would consider the SKHA. We showed that in this scenario the possible presence of the SKHA would lower the excitation temperature of the hyperfine doublet (the spin temperature) in two ways. First, by lowering the kinetic gas temperature to some effective value. Second, by lowering the color temperature of the radiation field in the Lyman series (responsible for the Wouthuysen-Field effect) to a much lower effective value. The combined effect of the SKHA seems to be sufficient for explaining the puzzling observational results by Bowman et al (2018).

It should be emphasized that this detailed alternative explanation of the Bowman et al (2018) results does not require or depend on the terminology introduced in paper I, such as "two flavors of hydrogen atoms" and "isohydrogen spin (isohyspin)". The detailed explanation of the Bowman et al (2018) results presented here stands on its own.

Further observational studies of the redshifted 21 cm radio line from the early Universe could help to find out which explanation is the most relevant.

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