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Alternative kind of hydrogen atoms as a possible explanation for the latest puzzling observation of the 21 cm radio line from the early Universe

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Abstract There is a puzzling astrophysical result concerning the latest observation of the absorption profile of the redshifted radio line 21 cm from the early Universe (as described in Bowman et al.). 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. Some explanations in the literature suggested a possible cooling of baryons either by unspecified dark matter particles or by some exotic dark matter particles with a charge a million times smaller than the electron charge. Other explanations required an additional radio background. In the present paper, we entertain a possible different explanation for the above puzzling observational result: the explanation is based on the alternative kind of hydrogen atoms (AKHA), whose existence was previously demonstrated theoretically, as well as by the analysis of atomic experiments. Namely, the AKHA are expected to decouple from the cosmic microwave background (CMB) much earlier (in the course of the Universe expansion) than usual hydrogen atoms, so that the AKHA temperature is significantly lower than that of usual hydrogen atoms. This seems to lower the excitation (spin) temperature of the hyperfine doublet (responsible for the 21 cm line) sufficiently enough for explaining the above puzzling observational result. This possible explanation appears to be more specific and natural than the previous possible explanations. Further observational studies of the redshifted 21 cm radio line from the early Universe could help to verify which explanation is the most relevant.

Key words: Cosmology: Early Universe — explanation of the puzzle of 21 cm radio line — Galaxies: intergalactic medium — Cosmology: observations — Cosmology: theory

1 INTRODUCTION

A puzzling observational result was published in Nature by Bowman et al. (2018a). The authors observed the 21 cm line (redshifted from the rest frequency of 1240 MHz to the frequency of 78 MHz) from the early Universe. They 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 modified excitation of the hydrogen 21 cm hyperfine structure line due to the ultraviolet light from stars formed in the early Universe that is expected to penetrate the primordial hydrogen gas. The puzzling result by Bowman et al. (2018a) was 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).

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 indicating the recorded absorption signal was indeed astronomical (rather than related to 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 dark matter. According to Barkana (2018), these dark matter particles must be lighter than 4.3 GeV (meaning that they could have, e.g., 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 & Holder (2018) proposed that the results by Bowman et al. (2018a) could be explained by a high-z radio background supplementing the 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 (Barkana 2018) was criticized by Mirocha & 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 $\sim$10 percent 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, in fairness it should be clarified that Barkana (2018) himself asserted that the subcase of weakly charged dark matter should probably be ruled out. Instead, Barkana (2018) assumed some kind of 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[1].

In the present paper, we suggest a possible alternative explanation for the puzzling observational result from Bowman et al. (2018a). It is based on the results of our previous paper (Oks 2001).

2 BRIEF DESCRIPTION OF THE ALTERNATIVE KIND OF HYDROGEN ATOMS (AKHA) AND OF EXPERIMENTAL EVIDENCE FOR THEIR EXISTENCE

In this section, we briefly summarize the results of Oks (2001). Solutions to the Dirac equation for an electron in a Coulomb field are common eigenfunctions of four operators (as is well known – see, e.g., the textbook by Rose 1961) – the Hamiltonian H, the projection J_z of the total angular momentum, the square of the total angular momentum J^2 and the following operator

$$K = \beta(2\mathbf{Ls} + 1)\,. \tag{1}$$

Here β is the Dirac matrix with rank four, whose nonzero elements are $\beta_{11} = \beta_{22} = 1$, $\beta_{33} = \beta_{44} = -1$; $\mathbf{L}$ and $\mathbf{s}$ are the operators of the orbital angular momentum and spin, respectively; $\mathbf{Ls}$ denotes the dot product (also known as the scalar product) of the latter two operators. Eigenvalues of the operators K and J^2 are connected as follows: $k = \pm(j + 1/2)$.

Hydrogen atoms in the stationary states have the following well-known energies.

$$E_{Nk} = mc^2 \left[1 + \alpha^2/[N + (k^2 - \alpha^2)^{1/2}]^2\right]^{-1/2}, \tag{2}$$

where N is the radial quantum number. For the ground state, the quantum numbers N and k have the following values.

$$N = 0, k = -1, \tag{3}$$

so that

$$E_{0,-1} = mc^2(1 - \alpha^2)^{1/2}. \tag{4}$$

For hydrogen atoms, the radial part $R_{Nk}(r)$ of the coordinate wave functions exhibits the following behavior at small r (see, e.g., the textbook by Rose 1961)

$$R_{Nk}(r) \;\; \propto \;\; 1/r^{1+s}, \qquad s = \pm(k^2 - \alpha^2)^{1/2}. \tag{5}$$

For the ground state, Equation (5) reduces to

$$R_{0,-1}(r) \propto 1/r^q, \quad q = 1 \pm (1 - \alpha^2)^{1/2}. \tag{6}$$

In Oks (2001), it was shown that, with allowance for the finite size of a proton, both the regular exterior solution corresponding to $q = 1 - (1 - \alpha^2)^{1/2}$ and the singular exterior solutions corresponding to $q = 1 + (1 - \alpha^2)^{1/2}$ are legitimate for the ground state[2]. The corresponding derivation in Oks (2001) was based *only* on the fact that in the ground state the eigenvalue of the operator K is $k = -1$. Therefore, actually the corresponding derivation from Oks (2001) is valid not just for the ground state, but for any state of hydrogenic atoms/ions characterized by the quantum number $k = -1$. Those are S-states ($l = 0$), specifically $^2S_{1/2}$ states. So, both the regular exterior solution corresponding to $q = 1 - (1 - \alpha^2)^{1/2}$ and the singular exterior solution corresponding to $q = 1 + (1 - \alpha^2)^{1/2}$ are legitimate not only for the ground state 1 $^2S_{1/2}$, but also for the states 2 $^2S_{1/2}$, 3 $^2S_{3/2}$ and so on, i.e., for the states n $^2S_{1/2}$ where $n = N + |k| = N + 1$ is the principal quantum number ($n = 1, 2, 3, ...$). Both the regular exterior solution corresponding to $q = 1 - (1 - \alpha^2)^{1/2}$ and the singular exterior solution corresponding to $q = 1 + (1 - \alpha^2)^{1/2}$ are legitimate also for the $l = 0$ states of the continuous spectrum.

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[1] Our paper should not be construed as a criticism of the Barkana (2018) paper: we greatly appreciate his paper and apply some numerical estimates from it.

[2] 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" solutions that have a weak singularity at the origin.

These theoretical results led to the possible existence of an alternative kind of hydrogen atoms (AKHA), corresponding to the singular solution outside the proton. It should be emphasized that *any n-state* of the AKHA and the *corresponding n-state* of the usual hydrogen atoms differ by the wave functions, but not by the energy, that is to say the energy is the same.

Moreover, Oks (2001) also presented the first experimental evidence for the existence of AKHA. Namely, for many decades there was a long-standing mystery about the huge discrepancy between the experimental and previous theoretical results concerning the high-energy tail of the linear momentum distribution in the ground state of hydrogen atoms. Previous theories predicted the tail to scale with the linear momentum p as $\sim 1/p^6$, while the corresponding experiments yielded the scaling of $\sim 1/p^k$, with a value of k close to 4. It was demonstrated in Oks (2001) that the allowance for AKHA eliminates this huge discrepancy. Thus, there were already both theoretical and experimental evidence for the existence of AKHA.

3 POSSIBLE ALTERNATIVE EXPLANATION FOR THE PUZZLING OBSERVATION OF THE 21 CM RADIO LINE FROM THE EARLY UNIVERSE

The possible existence of AKHA could provide an alternative explanation for the puzzling observational result from Bowman et al. (2018a). Bowman et al. (2018a) observed that the amplitude of the profile was more than a factor of two greater than the largest predictions, meaning that the primordial hydrogen gas was possibly much cooler than expected.

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 (with the latter being the excitation temperature of the hyperfine transition).

The standard expression for the spin temperature, as presented, e.g., in Field (1958) (see also, e.g., paper by Zaldarriaga et al. 2004 and review by Furlanetto et al. 2006) is the following

$$T_S = (T_{\rm CMB} + y_c T_K + y_{\rm Ly} T_{\rm Ly})/(1 + y_c + y_{\rm Ly}). \quad (7)$$

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, with y_c being the corresponding coupling coefficient. The 3rd term in the numerator relates to the Wouthuysen-Field effect: $T_{\rm Ly}$ is the color temperature of the radiation field in the Lyman series and $y_{\rm Ly}$ is the corresponding coupling coefficient. Physically, the Wouthuysen-Field effect is the transition between the hyperfine structure sublevels of the ground state facilitated by the absorption and the subsequent reemission of a photon of the Lyman series – mostly the Lyα photon.

The coupling coefficients in Equation (7) are as follows

$$y_c = C_{10} T_* /(A_{10} T_K), \quad y_{\rm Ly} = P_{10} T_* /(A_{10} T_{\rm Ly}). \quad (8)$$

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), $T_* = 0.068\,{\rm K}$, A_{10} is the corresponding Einstein coefficient and P_{10} is the direct de-excitation rate of sublevel 1 due to absorption of a Lyα 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≈17. Since the CMB temperature is $T_{\rm CMB} = 2.725(1 + z)\,{\rm K}$, then at z≈17 there was $T_{\rm CMB} \approx 49\,{\rm K}$. According to standard cosmology, at z≈17 there was $T_K \approx 7\,{\rm K}$, 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. (7)), the gas kinetic temperature T_K should not exceed $5.1\,{\rm K}$, as also noted by Barkana (2018).

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

Distinct from usual hydrogen atoms, AKHA do not have excited discrete states that can be coupled to the ground state via electric dipole radiation. (The AKHA still have two hyperfine sublevels in the ground state corresponding to the same 21 cm wavelength like usual hydrogen atoms.) This affects the spin temperature T_S as follows. The AKHA decouple from the CMB *earlier* than usual hydrogen atoms. Indeed, the AKHA decouple from the CMB when, in the course of the Universe expansion, the CMB temperature drops to the value $T_{{\rm CMB},A} = \alpha U_i$, 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 subscript A of $T_{{\rm CMB},A}$ stands for AKHA. By contrast, the usual hydrogen atoms decouple from the CMB at $T_{{\rm CMB},U} = \alpha E_{21}$, where $E_{21} = 3U_i/4$ is the energy difference between the first excited and ground states; the additional subscript U of $T_{{\rm CMB},U}$ stands for usual hydrogen atoms. To visualize: as the CMB temperature drops from $T_{{\rm CMB},A}$ to $T_{{\rm CMB},U}$, the CMB can still radiatively couple numerous discrete excited states of usual hydrogen atoms to the ground state and then at $T_{\rm CMB} < T_{{\rm CMB},U}$ there are no more excited states to be radiatively coupled to the ground state. For the

AKHA already at $T_{\rm CMB} < T_{{\rm CMB},A}$, there are no discrete excited states that can be coupled to the ground state via electric dipole radiation. Obviously, $T_{{\rm CMB},U}/T_{{\rm CMB},A} = E_{21}/U_i = 3/4$.

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 $T_{{\rm CMB},A}(a_1) = \alpha U_i$. Obviously, the kinetic gas temperature $T_{K,A}(a_1)$ of AKHA at $a = a_1$ is equal to $T_{{\rm CMB},A}(a_1)$, so that $T_{K,A}(a_1) = \alpha U_i$.

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 $T_{{\rm CMB},U}(a_2) = \alpha E_{21}$. Obviously, the kinetic gas temperature $T_{K,U}(a_2)$ of usual hydrogen atoms at $a = a_2$ is equal to $T_{{\rm CMB},A}(a_2)$, so that $T_{K,A}(a_2) = \alpha E_{21}$.

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

$$\begin{aligned} T_{K,A}(a_2)/T_{K,U}(a_2) &= T_{K,A}(a_2)/T_{\rm CMB}(a_2) \\ &= [T_{K,A}(a_2)/T_{K,A}(a_1)][T_{\rm CMB}(a_1)/T_{\rm CMB}(a_2)] \\ &= (a_1/a_2)^2(a_2/a_1) \\ &= a_1/a_2\,. \end{aligned} \tag{9}$$

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

$$T_{K,A}(a_2)/T_{K,U}(a_2) = E_{21}/U_i = 3/4. \tag{10}$$

Thus, at $a = a_2$, the AKHA fluid is colder than the fluid of usual hydrogen atoms. At some $a > a_2$, the two fluids come to thermal equilibrium with each other (due to the scattering of usual hydrogen atoms with AKHA), so that their effective (final) kinetic temperature is as follows[3].

$$\begin{aligned} T_{K,\rm eff} &= (T_{K,U}n_U + T_{K,A}n_A)/(n_U + n_A) \\ &= (T_{K,U} + T_{K,A}n_A/n_U)/(1 + n_A/n_U) \\ &= T_{K,U}[1 + (3/4)n_A/n_U]/(1 + n_A/n_U) \\ &= T_{K,U}\frac{[1 + (3/4)(\rho_A/\rho_U)\mu_U/m_A]}{[1 + (\rho_A/\rho_U)\mu_U/m_A]}, \end{aligned} \tag{11}$$

where n_U and n_A are the corresponding number densities, ρ_U and ρ_A are the corresponding mass densities, μ_U is the mean molecular mass of the (usual) neutral primordial gas and m_A is the atomic hydrogen mass ($m_A = 0.939\,{\rm GeV}$). By using the same numerical values as employed by Barkana (2018) (see, e.g., Eq. (3) from his paper), Equation (11) can be represented in the form

$$\begin{aligned} T_{K,\rm eff} &\approx T_{K,U}\frac{[1 + (3/4)(6\,{\rm GeV})/m_A]}{[1 + (6\,{\rm GeV})/m_A]}, \\ &\approx 0.79T_{K,U}, \end{aligned} \tag{12}$$

with the ratio ρ_A/ρ_U being ~ 5.

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

Thus, lowering the kinetic gas temperature to the effective value of $0.79T_{K,U}$ seems to be sufficient for explaining the observations by Bowman et al. (2018a).

4 CONCLUSIONS

Let us clarify upfront that this paper is not intended as a search for additional (astrophysical) evidence for the existence of AKHA – there is already experimental evidence for their existence based on the analysis of atomic experiments (as briefly described in the above Sect. 2 and presented in detail in Oks 2001). Instead, in this 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 AKHA.

We showed that in this scenario the possible presence of AKHA would lower the kinetic gas temperature to some effective value. This seems to be sufficient for explaining the puzzling observational results by Bowman et al. (2018a).

This explanation seems to be more specific and natural than adopting a possible cooling of baryons either by unspecified dark matter particles, as in Barkana (2018), or by some exotic dark matter particles with charge a million times smaller than the electron charge, as in Muñoz & Loeb (2018). Also, our explanation does not require an ad-

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[3] Because the AKHA have only S-states and the S-states are metastable, a significant share of the AKHA are in the excited $n^2S_{1/2}$ states, possibly including $n >> 1$ (in distinction to the usual hydrogen atoms). Since the characteristic size of these states scales as $\approx n^2$, so that the collisional cross-section scales as $\approx n^4$, then for the AKHA, collisions are much stronger than for the usual hydrogen atoms.

ditional radio background as suggested by Feng & Holder (2018) and by Ewall-Wice et al. (2018).

Further observational studies of the redshifted 21 cm radio line from the early Universe could help to discern which explanation is the most relevant[4].

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[4] We note in passing that the AKHA have their own 21 cm signal. In the dark ages (at $z\sim80$) the collisions are strong enough (see, e.g., Pritchard & Loeb 2012) that the spin temperature of the AKHA would be close to its kinetic temperature and one might see a significantly stronger 21 cm absorption signal than in the standard model.