DYNAMICS OF THE PRIMORDIAL HYDROGEN AND HELIUM (HeI) RECOMBINATION IN THE UNIVERSE

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Abstract. The dependences on z of fractional number densities of H⁺ and He⁺ ions are calculated with a proper allowance for two-photon decays of upper levels of hydrogen and parahelium and radiative transfer in intercombination line 2⁺P₁ ↔ 1⁺S₀ of helium. It is shown that for hydrogen this gives corrections for a degree of ionization in no more than a few percents but for helium this leads to a significant acceleration of recombination compared to the recent papers by Seager et al. (1999; 2000) where these effects were ignored.

Key words: cosmology, early universe, primordial helium, recombination, cosmic microwave background radiation (CMBR)

INTRODUCTION

Dynamics of primordial hydrogen and helium recombination was considered in a number of papers (see a brief review and references in Seager et al., 2000). However an actuality of new more accurate and detailed investigations of this process does not diminish. This is caused by a growing accuracy of new measurements of the microwave background radiation (CMBR) parameters with the aim to detect contributions of different new fundamental physical factors – dark matter, dark energy etc.

The most detailed calculations of the matter recombination in the Universe were fulfilled by Seager et al. (2000) by means of numerical solution of nonstationary equations for the level populations of hydrogen (300 levels), HeI (200 levels), HeII (100 levels) and for the number densities of electrons, protons, hydrogen negative ions H⁻ and molecules H₂ and H₂⁺ jointly with an equation for a matter temperature. With all this an average radiation intensity was taken to be the Planck function at all frequencies except for the ones in resonant lines for which the Sobolev approximation have been used. Collisional transitions were also taken into account along with radiative transitions but their contribution turned out to be negligible (as was obtained by a number of authors). It should be stressed that for HeI there were taken into account singlet states (parahelium) as well as triplet states (ortohelium).

The main result by Seager et al. (2000) concerning HeI recombination consists in that it goes much more slower than in equilibrium case (according to Saha equation) and slower than it was obtained by other authors. And as a main ”regulators” of recombination rate appear transitions from the second level of parahelium – two-photon ones (2⁺S₀ ↔ 1⁺S₀) and those of in a resonant line 2⁺P₁ ↔ 1⁺S₀. It turned out that (as in the case of hydrogen) the results of multilevel calculations are well described in terms of ”effective three level atom” (offered earlier for hydrogen by Peebles (1968) and by Zeldovich et al. (1968)) for parahelium with the usage

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of a corresponding fitting of the total recombination coefficient for the upper levels. In this connection Seager et al. (1999) created a simplified code recfast.for to compute recombination dynamics in terms of ”effective three level model” of hydrogen atoms (levels 1s, 2s, 2p + united continuum of upper levels) and helium atoms (levels 1s, 2s, 2p + united continuum of upper levels of parahelium).

In the present paper we investigate an influence of additional factors on the recombination dynamics of hydrogen and helium (HeI), namely – a contribution of two-photon transitions from upper levels of hydrogen and parahelium down to the ground state and radiative transfer in intercombination line \(2^3P_1 \leftrightarrow 1^1S_0\) of HeI, which were not taken into account explicitly in the code recfast.for by Seager et al. (1999) and probably were not taken into account in their multilevel calculations (Seager et al., 2000). We have considered how one can take into account these factors in a code recfast.for and have obtained a significant acceleration of the HeI recombination. We also have written our own computer code for calculation of HeI recombination dynamics with a proper allowance for all factors mentioned above and have obtained practically the same results as according to a modified code recfast.for.

THE MAIN EQUATIONS

Nonstationary equation for a degree of ionization of a chemical element (hydrogen or helium) \(y = N^+/N\) in the uniform expanding Universe can be written in a form

\[
(1 + z)H(z)N(z)\frac{dy}{dz} = \sum_i R_i, \tag{1}
\]

where \(N\) is a total number density of atoms and ions of an element, and \(N^+\) is a number density of its ions, \(H(z)\) is the Hubble factor, \(z\) is a redshift, \(R_i\) is a net rate of transitions from a level \(i\) down to the ground level 1 defining irreversible recombination. To pass from the time scale \(t\) to the scale of redshifts \(z\) we have used an equation \(dz/dt = -(1 + z)H(z)\).

Equation (1) holds in assumption that the level populations of excited states satisfy to the stationary equations of statistical equilibrium with number densities of electrons and ions available at the moment. This assumption is really fulfilled because the population of excited states is defined by permitted transitions (in the field of blackbody background radiation) while the number densities of electrons and ions are defined by much more slower two-photon transitions as well as by a ”red-shifting” of resonant photons to the longwave region due to the Universe expansion. We take into account only radiative transitions because as it commonly known (see e.g. Seager et al., 2000) collisional transitions are negligible. Then

\[
R_i = N_i(A_{i1} + B_{i1}J_{1i}) - N_1B_{1i}J_{1i}, \tag{2}
\]

where \(N_i\) is a population of a level \(i\), \(A_{i1}\), \(B_{i1}\) and \(B_{1i}\) are Einstein coefficients for transitions between level \(i\) and the first level, \(J_{1i}\) is some ”average” radiation intensity at the transition frequency.

Up to the present time the two-photon decay of the second level (2\(^1\)S\(_0\) for helium) and the ”red-shifting” of photons in the main resonance line (2\(^1\)P\(_1\) → 1\(^1\)S\(_0\) for helium) were considered as the only regulators of the recombination rate (see e.g. the paper by Seager et al. (2000) and references therein). However it is clear that similar processes should be taken into account for...
the upper levels of hydrogen and parahelium as well. Moreover, as it will be shown below, the
intercombination transition $2^{3}P_{1} \rightarrow 1^{1}S_{0}$ from the lower state of ortohelium takes a noticeable
part.

An expression (2) for two-photon transitions is rewritten as

$$R_{i}^{(2q)} = N_{i}A_{i1}^{(2q)} \left[ 1 - \frac{N_{1}g_{i}}{N_{i}g_{1}}e^{-\hbar \nu_{1i}/kT} \right] / \left( 1 - e^{-\hbar \nu_{1i}/kT} \right),$$

(3)

and it is supposed that the reverse process is a "capture" of two photons of a blackbody
radiation (with a temperature $T$) with a total energy equal to a transition energy $\hbar \nu_{1i}$. Here $\nu_{1i}$ is a transition frequency, $g_{i}$ is a statistical weight of a level $i$.

Assuming complete frequency redistribution under scatterings and using a boundary con-
dition that radiation intensity in a shortwave wing of a line strives to the Planck function we
have for resonant transitions

$$R_{i} = \beta_{1i}N_{i}A_{i1} \left[ 1 - \frac{N_{1}g_{i}}{N_{i}g_{1}}e^{-\hbar \nu_{1i}/kT} \right] / \left( 1 - e^{-\hbar \nu_{1i}/kT} \right),$$

(4)

where $\beta_{1k}$ is a probability of a photon escape from a process of scatterings due to an expansion
of the medium (Universe). It is defined through the Sobolev optical distance $\tau_{ik}$:

$$\beta_{ik} = \left( \frac{1}{\tau_{ik}} \right) \left( 1 - e^{-\tau_{ik}} \right), \quad 1/\tau_{ik} = \frac{4\pi}{hc} \frac{H(z)}{B_{ik}} \left( 1 - \frac{N_{k}g_{k}}{N_{i}g_{1}} \right)^{-1}. \quad (5)$$

Equations (4) and (5) correspond to the Sobolev approximation (Sobolev, 1947; see also a
review by Grachev (1994), devoted to some generalizations of this approximation), though
within the framework of available kynematics (a uniform expansion) it gives an exact solution.
Substitution of eq. (5) in eq. (4) gives

$$R_{i} = \frac{8\pi H(z) g_{1}N_{i}}{\lambda_{1i}^{3}} \left[ 1 - e^{-\tau_{1i}} \right] \frac{1 - (N_{1}g_{i}/N_{i}g_{1})e^{-\hbar \nu_{1i}/kT}}{1 - N_{1}g_{1}/N_{i}g_{i}} / \left( 1 - e^{-\hbar \nu_{1i}/kT} \right),$$

(6)

where the wavelength of transition $\lambda_{1i} = c/\nu_{1i}$. So far as at the begining of He$^{+}$
recombination (for $z \approx 2700$) we already have for energies and populations of excited states $\hbar \nu_{1i} \gg kT$ and $N_{i} \ll N_{1}$ respectively then in eqs. (3) and (6) in the last multiplier one can neglect by an
exponential term compared to unity and in eq. (6) – also by the second term in the denominator
of the fraction. Then the equations mentioned above are rewritten as

$$R_{i}^{(2q)} = N_{i}A_{i1}^{(2q)} \left[ 1 - (N_{1}g_{i}/N_{i}g_{1})e^{-\hbar \nu_{1i}/kT} \right],$$

(7)

and

$$R_{i} = \frac{8\pi H(z) g_{1}N_{i}}{\lambda_{1i}^{3}} \frac{g_{i}N_{i}}{N_{i}^{2}} \left[ 1 - e^{-\tau_{1i}} \right] \left[ 1 - (N_{1}g_{i}/N_{i}g_{1})e^{-\hbar \nu_{1i}/kT} \right],$$

(8)

where $N_{1} = N - N^{+}$ because an overwhelming part of hydrogen an helium neutral atoms are
in the ground state at the epoch of recombination.

Thus the problem is reduced to a solution of eq. (1) with $R_{i}$ at the righthand side according
to eqs. (7) and (8) while the populations of excited states appearing in the righthand sides of
these equations are determined from equations of statistical equilibrium for the current values of electrons and ions number densities. It should be noted that such an approach was used by us earlier (Grachev and Dubrovich, 1991) under the calculations of hydrogen recombination within the framework of 60-level model of atoms. However during an almost all time of helium recombination ($z = 2700 – 1800$) the radiation temperature remains high enough for populations of HeI excited states (which are less than 5 eV away from the continuum) to be close to equilibrium ones (relative to the continuum) i.e. were defined by Boltzmann – Saha equations with the electron temperature equal to the radiation temperature ($T_e = T$):

$$
N_i = N_e N^+ \frac{g_i}{2g^+ g(T_e)} e^{h\nu_{ic}/kT_e} ,
$$

$$
g(T_e) = (2\pi m k T_e)^{3/2}/\hbar^3 ,
$$

where $N_e$ is an electron number density, $h\nu_{ic}$ is a threshold energy of ionization from a level $i$. Then eqs. (10) and (11) are rewritten in the form

$$
R_i^{(2q)} = \frac{N(1 - y)}{r_1} g_i A_i^{(2q)} e^{h\nu_{ic}/kT_e} (1 - r_1 e^{-h\nu_{ic}/kT_e}) ,
$$

$$
R_i = \frac{8\pi H(z)}{\lambda_{ii}^3} \frac{1}{r_1} e^{h\nu_{ic}/kT_e} (1 - e^{-\tau_i})(1 - r_1 e^{-h\nu_{ic}/kT_e}) ,
$$

where $r_1 = (2g^+/g_1)g(T_e)/(N_e y)$.

In view of importance of allowance for two-photon transitions from upper levels of helium we adduce below a brief derivation of equations for transition probabilities according to Dubrovich (1987). The process of simultaneous emission of two photons by excited atoms is well-known long ago and is described in text-books (see Berestetskii et al., 1989). Well-known long ago is also the role of this process in the hydrogen atom for the continuum radiation formation in the interstellar medium (Kipper, 1950) and in the early Universe (Zeldovich et al., 1968). However, in these specific cases only one state of hydrogen is taken into account namely – $2s$. At the same time, as it was shown by Dubrovich (1987), for some values of a medium and background radiation parameters similar decays of upper levels can give noticeable and in some cases a main contribution. Here we will consider this question only in the context of hydrogen and helium recombination in the early Universe.

From quantum-mechanical selection rules it follows that actually we should consider $is$ and $id$ states only. An exact expression for a probability of spontaneous two-photon transition is written according to Berestetskii et al. (1989) (eqs. (59.28)) in the form

$$
dW = \frac{2^{10}\pi^6 \nu^3 \nu'^3}{9h^2 c^6} \sum_{\nu, \nu'} \left[ \frac{(d_\alpha)_{1s,\nu'}(d_\beta)_{\nu',\nu} + (d_\beta)_{1s,\nu'}(d_\alpha)_{\nu',\nu}}{\nu, \nu', \nu + \nu'} \right]^2 d\nu ,
$$

where $\nu + \nu' = \nu_{il,1s}$, subscripts $il$, $i'l'$ and 1s number initial, intermediate and final atom states ($i$ is a main quantum number, $l$ is an orbital moment), $(d_\alpha)_{il,\nu'}$ is a matrix element of a dipole moment, $\alpha$ and $\beta$ number spatial components of a dipole moment vector, $\nu$ and $\nu'$ are the frequencies of emitted photons, $h$ is the Planck constant, $c$ is the velocity of light. Sharp maxima in eq. (12) under $\nu$ or $\nu' = \nu_{il'}$ correspond to resonances of a cascade transition from an excited level down with an emission of photons of a discrete spectrum of an atom. Corresponding to them very large transition probability leads in specific conditions of quasi-equilibrium with
a blackbody radiation to a very high probability of a reverse capture of the same photons. Strictly speaking this question must be learned more thoroughly because "not entirely" resonant transition, but not far from a resonance, can give contribution under the scheme of "a Lyman quantum escape into the wing". In principle this will lead to an additional speeding-up of recombination. However a thorough analysis requires a radiative transfer solution which we intend to obtain in the next paper. Here we will consider only transitions giving continuous distribution of emitted photons i.e. we shall assume that $\nu_{i1} - \nu' \sim \nu$. So an obtained rate of recombination can be regarded as a lower estimate.

Because we are interested in a two-photon transition to a final state with a zero orbital moment ($s$ state) then $l$ may be equal only 0 ($s$ state) or 2 ($d$ state) according to selection rules for dipole transitions. For both cases the value of $l'$ may be equal only 1 ($p$ state). In this case an expression for $W$ can be simplified significantly. It can be simplified still more if to notice that according to summation rule for dipole transitions [Berestetskii et al., 1989, eq. (52.8)] nearly 90% of contribution is due to transitions with $i' = i$ [Berestetskii et al., 1989, eq. (52.6)].

As a result we come to an expression for a matrix element structure well-known for the 2$s$−1$s$ transition in a hydrogen atom. In our case to calculate $W$ we need only in a proper allowance for the frequency difference i.e. we must multiply $A_{2s,1s}$ by $(\nu_{i1}/\nu_{21})^5$ and sum up the two ways of decay (from $s$ and $d$ sublevels) with a proper allowance for their statistical weights. Finally we obtain for hydrogen the following expression:

$$W_{H} \equiv g_i A_{i1}^{(2q)} = 54 \cdot A_{2s,1s} \cdot [(i - 1)/(i + 1)]^{2i} (11i^2 - 41)/i. \tag{13}$$

For large $i$ we have approximately $W_{H} = 89i$ s$^{-1}$. The growth of $W_{H}$ with the level number takes place actually up to a some value $i$. This is caused by an existence of the limit of the dipole approximation applicability. Namely the wavelength of emitted photon (which is in our case $\sim 2/\nu_{i1} \to \text{const}$) must be greater than the size of an excited state orbit ($\sim i^2$). For hydrogen $i_{\text{max}} \sim 30$ (Beigman and Syrkin, 1983).

Similar consideration can be carry out also for decays of hydrogen-like states of HeI. For $i > 6 - 7$ such an approximation is quite rightfull for the matrix elements $i(s,d) - ip$. It becomes sufficiently accurate for our aims also for the square of the matrix element $ip \to 1s$ if we introduce correction multiplier $1.15 - 1.20$ which follows from comparing of oscillator strengths of these transitions for HeI and for hydrogen. And of course eq. (13) must be renormalized again with a proper allowance for the frequency of emitted photons i.e. $W$ for hydrogen must be multiplied by $(24.6/13.6)^5 = 19.4$. Finally we have for $W_{\text{HeI}}$:

$$W_{\text{HeI}} \equiv g_i A_{i1}^{(2q)} = 1045 \cdot A \cdot [(i - 1)/(i + 1)]^{2i} (11i^2 - 41)/i. \tag{14}$$

A limiting condition for $i$ is here the same as for the case of hydrogen. If dipole approximation is applicable (for $i < 40$) then one should take $A = 10$ s$^{-1}$ in eq. (14). Otherwise there is an uncertainty connected with poorly known (both theoretically and experimentally) dependence of $A$ on a level number. Most probably a contribution of these levels ($i > 40$) is not very large. Approximately it can be taken into account taking $A = 12$ s$^{-1}$. However for precise measurements of the power spectrum with the aim to obtain information about weak but very important factors an additional investigation of $A$ is necessary.

An influence of two-photon decays of upper levels on the dynamics of recombination must be much more significant for HeI than for hydrogen. This is caused by two circumstances: first –
by much more absolute value of $W$ and, second, – by the fact that relation between populations of 2$s$-level and Rydberg levels significantly differs since a ratio of these populations contains the Boltzmann factor $\exp(-h\nu_{ic}/kT)$. For hydrogen this factor is equal approximately $3 \cdot 10^{-5}$ while for HeI it is larger approximately at 85 times since an absolute values of energy differences for HeI are approximately the same but the temperature at which it recombines is significantly higher. A contribution to a rate of destruction of ”superfluous” Lyman quantums is defined by a product of a population on a decay probability.

We wrote computer programme to solve eq. (1) for helium with the terms in the righthand side of the form (10) and (11) and along with the two-photon transitions from the second level of parahelium ($i = 2s \leftrightarrow 1$) we also took into account transitions from upper levels ($i = 6 \rightarrow 40$) which were considered as hydrogen-like (Rydberg ones). For their energy counted from a threshold of ionization we take $h\nu_{ic} \approx 1$ Ry and for Einstein coefficients we use eq. (14). Moreover along with the resonant transition from the second level of parahelium $i = 2p \leftrightarrow 1$ (thereafter we wright for the sake of simplicity $i = 2p \leftrightarrow 1$) it was also taken into account spin-forbidden one-photon transition from the second level of orthohelium: $2p_3P_1 \leftrightarrow 1S_0$ for which we use the value of Einstein coefficient $A_{2p_3P_1,1S_0} = 233$ s$^{-1}$ according to Lin et al., 1977. It should be stressed that for the degree of ionization of hydrogen which is contained in equation $N_e = N_H + N_{He}$ we have used Saha equation (equilibrium ionization) which holds for sufficiently large $z$ where the main HeI recombination takes place.

We also introduced corresponding additions into the programme recfast.for by Seager et al. (1999) in which two-photon transitions were taken into account only from the second level ($i = 2s \leftrightarrow 1$) and Einstein coefficients $A_{2s,1}$ for hydrogen and parahelium ($\Lambda_H$ and $\Lambda_{HeI}$ in notations by Seager et al., 1999) $\Lambda_H = 8.22$ s$^{-1}$ and $\Lambda_{HeI} = 51.3$ s$^{-1}$. To take into account two-photon transitions from upper levels it needs evidently according to eq. (10) to make a replacement

$$\Lambda \rightarrow \Lambda + \sum_{i=0}^{i_N} g_i A_{1i}^{(2q)} e^{h(\nu_{ic} - \nu_{2s,c})/kT}.$$  

Further, in the programme recfast.for a contribution of transition $i = 2p \leftrightarrow 1$ for hydrogen and parahelium is described by the factors $K_H$ and $K_{HeI}$ respectively where $K = \lambda_{1,2p}/[8\pi H(z)]$ so that a contribution of other lines (for one-photon transitions) can be taken into account (in accordance with eq. (11)) by the following replacement:

$$\frac{1}{K} \rightarrow \frac{1}{K} \left[ 1 + \sum_i (\lambda_{1,2p}/\lambda_{1i})^3 e^{h(\nu_{ic} - \nu_{2s,c})/kT}(1 - e^{-\tau_{1i}})/(1 - e^{-\tau_{1,2p}}) \right],$$  

and for the main resonant transition during the whole recombination an optical depth $\tau_{1,2p} \gg 1$ so that the corresponding exponential term can be omitted.

As the computations have shown the results obtained under our own programme and under the programme recfast.for modified as pointed above are practically coincide (for the values of parameters of the Universe model accepted now).

RESULTS OF COMPUTATIONS

Parameters in the problem are equilibrium temperature of the microwave background $T_0$, Hubble factor $H_0$, the ratio of the total density to the critical one $\Omega_{total}$, the ratio of the baryon
Figure 1: The profiles of helium ionization degree. Numbers near the curves: 1 – only “main” transitions $2s \leftrightarrow 1$ and $2p \leftrightarrow 1$ of parahelium, 2 – main + transition in a line of ortohelium, 3 – main + transitions from upper levels of parahelium ($A = 10 \text{ s}^{-1}$), 4 – main + both additional ways (continuous line – $A = 10 \text{ s}^{-1}$, broken line – $A = 12 \text{ s}^{-1}$), 5 – equilibrium case (Saha equation). Values of parameters: $\Omega_{\text{total}} = 1$, $T_0 = 2.728 \text{ K}$, $H_0 = 70 \text{ (km/s)/Mpc}$, $\Omega_B = 0.04$, $\Omega_{\text{DM}} = 0.26$, $\Omega_\Lambda = 0.7$. Helium content (by mass) $Y = 0.24$.

density to the critical one $\Omega_B$, the ratio of the dark matter to the critical one $\Omega_{\text{DM}}$, the ratio of the density caused by the $\Lambda$-term to the critical one $\Omega_\Lambda$ at the present day epoch and the content of the primordial helium (by mass) $Y$. Test computations were fulfilled for $T_0 = 2.728 \text{ K}$, $\Omega_{\text{total}} = 1$, $Y = 0.24$, $H_0 = 70 \text{ (km/s)/Mpc}$, $\Omega_B = 0.04$, $\Omega_{\text{DM}} = 0.26$ and $\Omega_\Lambda = 0.7$.

Fig. 1 shows the results of computations. Numbers 1, 2, 3 and 4 correspond to a succesive allowance for additional ways of irreversible helium recombination: 1 – only ”main” transitions $2s \leftrightarrow 1$ and $2p \leftrightarrow 1$ of parahelium, 2 – main + transition in ortohelium line, 3 – main + transitions from the upper levels ($i = 6 - 40$) of parahelium for $A = 10 \text{ s}^{-1}$ in eq. (14), 4 – main + both additional ways (continuous line – for $A = 10 \text{ s}^{-1}$ in eq. (14), broken line – for $A = 12 \text{ s}^{-1}$, 5 – equilibrium case (Saha equation). One can see from the Fig. 1 that succesive allowance for additional ways of irreversible recombination significantly enhances the rate of HeI recombination. At the same time our results practically coincide (undistinguished on the Figure) with the ones obtained under the programme recfast.for modified by the way stated in the preceeding section.

With the aid of the programme recfast.for we took into account additional ways of irreversible recombination for hydrogen too. These ways are two-photon transitions from the levels $i = 3 - 40$ down to the first level and radiative transfer in the corresponding Lyman lines. The first way was taken into account according to eqs. (15) and (13) and the second – according to eq. (16) while exponents in round brackets in this equation were omitted because the Sobolev
Figure 2: An influence of additional transitions on the profile of hydrogen ionization degree $y_H = N_{H^+} / N_H$. On the ordinate axis is $r_H = 2(y_{H}^{\text{old}} - y_{H}^{\text{new}})/(y_{H}^{\text{old}} + y_{H}^{\text{new}})$, where $y_{H}^{\text{old}}$ corresponds to "main" transitions $2s \leftrightarrow 1$ and $2p \leftrightarrow 1$ only, and $y_{H}^{\text{new}}$ corresponds to main + transitions from upper levels. Values of parameters are the same as for the Fig. 1.

thicknesses in Lyman lines $\tau_{1i} \gg 1$. It turned out that the first way leads to decrease of hydrogen ionization degree by no more than 4.2% and the second – by no more than 1% and in sum – by no more than 4.3% (for the same values of the model parameters as in the case of helium). Results are in the Fig. 2. It should be stressed that we have fulfilled in addition similar computations using our own programme (Grachev and Dubrovich, 1991) based on solution of eq. (1) jointly with equations of statistical equilibrium for the level populations of hydrogen atoms within the framework of 60-level model of an atom and we have obtained practically the same result as in the Fig. 2.

CONCLUSIONS

Computations of hydrogen and HeI recombination dynamics are made with a proper allowance for two-photon decays of upper levels of hydrogen and parahelium and radiative transfer in intercombination line $2\,^2P_1 \leftrightarrow 1\,^1S_0$ of helium. It is shown that this leads to changes of hydrogen recombination rate accessible to discover under the programme "PLANCK". Obtained results are important for a correct evaluation of small factors defined by an existence of dark matter, baryon and nonbaryon parts of the substance mass in the Universe, relativistic (at the moment of recombination) particles – neutrino and possibly axions and other low-mass low-interacting particles. It is shown that an allowance for new factors of destruction of suprathermal Lyman photons significantly accelerates HeI recombination compared to predictions according to the papers by Seager et al. (1999; 2000) where these effects were not taken into account. This is also important for the correct estimation of the helium role in the hydrogen
recombination. Moreover it is very important for determination of profiles and intensities of hydrogen and HeI recombination lines. In particular an important role of high levels in irreversible recombination leads to an appearance of absorption lines in the CMBR spectrum caused by transitions in Balmer lines of hydrogen and in different more complex lines of helium. This moment is principally important from the point of view of detection and identification of such lines. As a next step in this direction it is necessary to consider a role of weakly nonresonant transitions from upper levels which can lead to an additional acceleration of recombination for hydrogen as well as for helium.

As concerns an influence of our refinements of HeI recombination dynamics on the theoretical power spectra of microwave background radiation it can be estimated very roughly from Fig. 17 in the paper by Seager et al. (2000) where their results are compared with the results by Hu et al. (1995) obtained actually assuming equilibrium HeI ionization (according to Saha equation). So, since our curve of variation of HeI ionization degree lies practically "in the middle" between equilibrium one (according to Saha equation) and that from Seager et al. (see Fig. 1) then one can expect that with our refinements the discrepancy with the results by Hu et al. will become 2 times smaller (e.g. for multipole \( l = 1500 \) it will be 1% instead of 2%). At the same time an uncertainty of \( A \) (see Fig. 1, curves 4) estimated approximately at 20% should give the same relative uncertainty for correction of theoretical power spectrum.

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