Intergalactic heating by Ly\(\alpha\) photons including hyperfine structure corrections

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(Dated: June 1, 2021)

ABSTRACT

Ly\(\alpha\) photons from the first radiating sources in the Universe play a pivotal role in 21-cm radio detections of Cosmic Dawn and the Epoch of Reionization. Comments are provided on the effect of the hyperfine structure of hydrogen on the rate of heating or cooling of the Intergalactic Medium by Ly\(\alpha\) photons.

Keywords: cosmology: theory – dark ages, reionization, first stars – intergalactic medium – radiative transfer – radio lines: general – scattering

1. INTRODUCTION

The role of the Wouthuysen-Field effect in the anticipated 21-cm radio detection of the Epoch of Reionization and Cosmic Dawn depends on the radiative transfer of Ly\(\alpha\) photons in a cosmological context. In addition to decoupling the hyperfine spin temperature of the hydrogen component of the diffuse Intergalactic Medium (IGM) from the Cosmic Microwave Background (CMB), Ly\(\alpha\) radiation is also able to heat or cool the still neutral hydrogen through atomic recoils (Madau et al. 1997; Chen & Miralda-Escudé 2004). Precision predictions for the radiative transfer depend on the hyperfine structure of hydrogen (Chuzhoy & Shapiro 2006; Hirata 2006). The treatment of Ly\(\alpha\) photon heating of the IGM in Meiksin (2006) is extended here to include the role of the hyperfine structure of hydrogen. A much smaller contribution of the hyperfine structure to the heating rate of the IGM is found than has been previously suggested.

2. HEATING RATE

The Wouthuysen-Field effect changes the number density \(n_1\) of hydrogen atoms in the upper hyperfine \(n = 1\) level at the rate \(Dn_1/Dt = n_0P_{01}^\alpha - n_1P_{10}^\alpha\), where \(n_0\) is the number density in the lower hyperfine state, \(P_{01}^\alpha = (4/27)P_{\alpha}\) is the de-excitation rate of the upper hyperfine level for total Ly\(\alpha\) photon scattering rate \(P_{\alpha}\), and \(P_{01}^\alpha = 3\exp(-T_{\alpha}/T_{L}^\alpha)P_{10}^\alpha\) is the excitation rate for ‘light’ or ‘color’ temperature \(T_{L}^\alpha\) of the Ly\(\alpha\) photons (Field 1958; Meiksin 2006). To order \(T_{s}/T_{S}\) and \(T_{s}/T_{L}^\alpha\), this is \(Dn_1/DT \simeq \frac{1}{9}n_HP_{\alpha}(T_{s}/T_{S})(1 - T_{S}/T_{L}^\alpha)\). Including excitation by the CMB, the total rate equation becomes

\[
\frac{Dn_1}{Dt} \simeq -n_1 \left(A_{10} + P_{01}^{\text{CMB}}\right) + n_0P_{01}^{\text{CMB}} + \frac{1}{9}n_HP_{\alpha} \left(\frac{T_{s}}{T_{S}}\right) \left(1 - T_{S}/T_{L}^\alpha\right),
\]

where \(P_{01}^{\text{CMB}}\) and \(P_{01}^{\text{CMB}}\) are the excitation and de-excitation rates, respectively, by CMB photons.

Extending the analysis of Meiksin (2006) to include the hyperfine structure splittings gives for the rate of change of the Ly\(\alpha\) photon radiation energy density

\[
\frac{Du_{\alpha}}{Dt} = -n_HcB_{\alpha} \int_0^\infty d\nu \langle Q \rangle \varphi_{\alpha}(\nu)u_{\nu} = -P_{\alpha}n_Hh\nu_{\alpha}\frac{h\nu_{\alpha}}{m_e c^2} \left(1 - \frac{T_K}{T_{L}^\alpha}\right) - \frac{1}{9}P_{\alpha}n_Hh\nu_{\alpha} \left(\frac{T_{s}}{T_{S}}\right) \left(1 - \frac{T_{S}}{T_{L}^\alpha}\right),
\]

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where $n_\text{H}$ is the total hydrogen number density, $u_\nu$ is the radiation energy density, $\langle Q \rangle$ is the total mean frequency shift through the Ly$\alpha$ resonance and $P_\alpha = (c/4\pi)B_\alpha \int_0^\infty d\nu \varphi_\alpha(\nu)u_\nu$ is the total Ly$\alpha$ scattering rate per atom with (upward) absorption coefficient $B_\alpha$ and Voigt profile $\varphi_\alpha$ centred at the average Ly$\alpha$ resonance transition frequency $\nu_\alpha$, and $\nu_{10}$ is the frequency of the 21-cm transition. The first term arises from atomic recoils of Ly$\alpha$ photons and the second is the average energy spent changing the internal energy of the atoms, noting that the Ly$\alpha$ radiation field loses energy $h\nu_{10}$ per Ly$\alpha$ photon scattering that excites the $n = 1$ upper hyperfine level, and gains energy $h\nu_{10}$ per de-excitation. It has been assumed that virtually all the hydrogen atoms are in the $n = 1$ state. Here, $T_K$ is the gas kinetic temperature and $T_S$ is the spin temperature, defined by the relative abundance of atoms in hyperfine states 1 and 0 by $n_1/n_0 = 3 \exp(-T_*/T_S)$, where $kT_* = h\nu_{10}$. The light temperature $T_L^\alpha$ is given by $T_L^\alpha = \int_0^\infty d\nu \varphi_\alpha(\nu)/[\int_0^\infty d\nu \varphi_\alpha(\nu)/T_\alpha(\nu)]$ for $T_\alpha(\nu) = -(h/k)/(d\log u_\nu/d\nu)$ (Meiksin 2006). Eq. (2) agrees with the findings of Chuzhoy & Shapiro (2006) when their result is integrated over the radiation field and Voigt profile.

Similarly, the rate of change of the CMB radiation field energy density arising from 21-cm photon scattering is

$$\frac{D_u}{Dt} = - P_{\text{CMB}} n_\text{H} h \nu_{10} h \nu_{10},$$

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where $P_{\text{CMB}} = (c/4\pi)B_{\text{CMB}} \int_0^\infty d\nu \varphi_{\text{CMB}}(\nu)u_\nu$ and $\varphi_{10}$ is the Voigt absorption profile for the 21-cm transition. The excitation rate $P_{01}^{\text{CMB}}$ is similarly defined in terms of $B_{01}$. Here, $T_L^{\text{CMB}}$ is the CMB light temperature for 21-cm photon scattering, defined analogously to $T_L^\alpha$ for Ly$\alpha$ photon scattering. The first term in Eq. (3) arises from atomic recoils of 21-cm photons and the remaining from the change in the internal energy of the atoms. The rate $P_{\text{CMB}} = P_{01}^{\text{CMB}}/4$, assuming $n_0 \approx n_1/4$. Combining with the Ly$\alpha$ photon radiation field, the total rate of change of the energy density of the radiation field is $Du/Dt = Du^{\text{CMB}}/Dt + Du^{\text{CMB}}/Dt$, corresponding to a heating rate of the IGM of

$$G_H = - \left( \frac{D_u^{\text{CMB}}}{Dt} + \frac{D_u}{Dt} \right) = P_\alpha n_\text{H} h \nu_\alpha h \nu_{10},$$

assuming the hyperfine levels have reached a steady state, $Du_{10}/Dt = 0$ from Eq. (1). Only the atomic recoils contribute to heating the IGM. In the absence of flow fields, the hyperfine structure shifts $T_L^{\text{CMB}}$ from $T_K$ slightly towards $T_S$ (Chuzhoy & Shapiro 2006; Hirata 2006), while the presence of a flow field generally results in $T_L^{\text{CMB}} \neq T_K$ (Chen & Miralda-Escudé 2004; Meiksin 2006). In the Rayleigh-Jeans approximation, the effective light temperature of the CMB 21-cm photons for scattering is $T_L^{\text{CMB}} \approx -T_*/2$. For $T_* \ll T_K$, the characteristic heating time of the IGM by the CMB is $(3/P_{01}^{\text{CMB}})(n_\text{H} h^2/C MB) \approx 10^2 s/(1 + z)$ at redshift $z$, and so negligible. It is much slower than the rate claimed by Venumadhav et al. (2018), based on the last two terms of Eq. (3) alone, as the canceling term from the hyperfine structure contribution to the energy transfer of the Ly$\alpha$ photons in Eq. (2) was not accounted for there. Allowing for atomic collisional excitation and de-excitation of the hyperfine levels makes only a slight modification (Hirata & Sigurdson 2007), which will also cancel in statistical equilibrium.

The absence of heating without atomic recoils may have been anticipated from the start since, without recoils, the CMB and Ly$\alpha$ radiation fields only rearrange the energy levels within the atoms. When not in a steady state, energy exchange with the CMB and Ly$\alpha$ radiation fields may change the internal excitation energy of the atoms, but, without recoils, this does not correspond to heating the gas.

ACKNOWLEDGMENTS

The author thanks S. Mittal and G. Kulkarni for exchanges that led the author to revisit the subject. The author also acknowledges support from the UK Science and Technology Facilities Council, Consolidate Grant ST/R000972/1.

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