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Intergalactic heating by Lyα photons including hyperfine structure corrections

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ABSTRACT

Lyα 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 Lyα 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 Lyα 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), Lyα 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 Lyα 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, $P_{10}^\alpha = (4/27)P_\alpha$ is the de-excitation rate of the upper hyperfine level for total Lyα photon scattering rate P_α, and $P_{01}^\alpha = 3\exp(-T_*/T_L^\alpha)P_{10}^\alpha$ is the excitation rate for 'light' or 'color' temperature T_L^α of the Lyα photons (Field 1958; Meiksin 2006). To order T_*/T_S and T_*/T_L^α, this is $Dn_1/Dt \simeq (1/9)n_{\rm H}P_\alpha(T_*/T_S)(1 - T_S/T_L^\alpha)$. Including excitation by the CMB, the total rate equation becomes

$$\frac{Dn_1}{Dt} \simeq -n_1\left(A_{10} + P_{10}^{\rm CMB}\right) + n_0P_{01}^{\rm CMB} + \frac{1}{9}n_{\rm H}P_\alpha\left(\frac{T_*}{T_S}\right)\left(1 - \frac{T_S}{T_L^\alpha}\right), \tag{1}$$

where $P_{01}^{\rm CMB}$ and $P_{10}^{\rm CMB}$ 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 Lyα photon radiation energy density

$$\frac{Du^\alpha}{Dt} = -n_{\rm H}c\frac{B_\alpha}{4\pi}\int_0^\infty d\nu\,\langle Q\rangle\varphi_\alpha(\nu)u_\nu = -P_\alpha n_{\rm H}h\nu_\alpha\frac{h\nu_\alpha}{m_{\rm H}c^2}\left(1 - \frac{T_K}{T_L^\alpha}\right) - \frac{1}{9}P_\alpha n_{\rm H}h\nu_{10}\frac{T_*}{T_S}\left(1 - \frac{T_S}{T_L^\alpha}\right), \tag{2}$$

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where $n_{\rm H}$ is the total hydrogen number density, u_ν is the radiation energy density, $\langle Q\rangle$ is the total mean frequency shift through the Lyα resonance and $P_\alpha = (c/4\pi)B_\alpha\int_0^\infty d\nu\varphi_\alpha(\nu)u_\nu$ is the total Lyα scattering rate per atom with (upward) absorption coefficient B_α and Voigt profile φ_α centred at the average Lyα resonance transition frequency ν_α, and ν_{10} is the frequency of the 21-cm transition. The first term arises from atomic recoils of Lyα photons and the second is the average energy spent changing the internal energy of the atoms, noting that the Lyα radiation field loses energy $h\nu_{10}$ per Lyα 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^α is given by $T_L^\alpha = \int_0^\infty d\nu\, u_\nu\varphi_\alpha(\nu)/[\int_0^\infty d\nu\, u_\nu\varphi_\alpha(\nu)/T_u(\nu)]$ for $T_u(\nu) = -(h/k)/(d\log u_\nu/d\nu)$ (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

$$\frac{Du^{\rm CMB}}{Dt} = -P_{\rm CMB}n_{\rm H}h\nu_{10}\frac{h\nu_{10}}{m_{\rm H}c^2}\left(1-\frac{T_K}{T_L^{\rm CMB}}\right) + n_1h\nu_{10}\left(A_{10}+P_{10}^{\rm CMB}\right) - n_0h\nu_{10}P_{01}^{\rm CMB}, \tag{3}$$

where $P_{10}^{\rm CMB} = (c/4\pi)B_{10}\int_0^\infty d\nu\varphi_{10}(\nu)u_\nu$ and φ_{10} is the Voigt absorption profile for the 21-cm transition. The excitation rate $P_{01}^{\rm CMB}$ is similarly defined in terms of B_{01}. Here, $T_L^{\rm CMB}$ is the CMB light temperature for 21-cm photon scattering, defined analogously to T_L^α for Lyα 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 $P_{\rm CMB} = P_{01}^{\rm CMB}/4$, assuming $n_0 \simeq n_{\rm H}/4$. Combining with the Lyα photon radiation field, the total rate of change of the energy density of the radiation field is $Du/Dt = Du^\alpha/Dt + Du^{\rm CMB}/Dt$, corresponding to a heating rate of the IGM of

$$G_H = -\left(\frac{Du^\alpha}{Dt}+\frac{Du^{\rm CMB}}{Dt}\right) = P_\alpha n_{\rm H}h\nu_\alpha\frac{h\nu_\alpha}{m_{\rm H}c^2}\left(1-\frac{T_K}{T_L^\alpha}\right) + P_{\rm CMB}n_{\rm H}h\nu_{10}\frac{h\nu_{10}}{m_{\rm H}c^2}\left(1-\frac{T_K}{T_L^{\rm CMB}}\right) \tag{4}$$

assuming the hyperfine levels have reached a steady state, $Dn_1/Dt = 0$ from Eq. (1). Only the atomic recoils contribute to heating the IGM. In the absence of flow fields, the hyperfine structure shifts T_L^α from T_K slightly towards T_S (Chuzhoy & Shapiro 2006; Hirata 2006), while the presence of a flow field generally results in $T_L^\alpha \neq T_K$ (Chen & Miralda-Escudé 2004; Meiksin 2006). In the Rayleigh-Jeans approximation, the effective light temperature of the CMB 21-cm photons for scattering is $T_L^{\rm CMB} \simeq -T_*/2$. For $T_* \ll T_K$, the characteristic heating time of the IGM by the CMB is $(3/P_{01}^{\rm CMB})(m_{\rm H}c^2/h\nu_{10}) \simeq 10^{27}\,{\rm s}/(1+z)$ at redshift z, and so negligible. It is much slower than the rate claimed by Hirata & Sigurdson (2007) 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 Lyα photons in Eq. (2) was not accounted for there.

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

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