Cyclotron emission effect on CMB spectral distortions

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Abstract. We investigated the role of the cyclotron emission (CE) associated to cosmic magnetic fields (MF) on the evolution of cosmic microwave background (CMB) spectral distortions. We computed the photon and energy injection rates by including spontaneous and stimulated emission and absorption. These CE rates have been compared with those of bremsstrahlung (BR) and double Compton scattering (DC), for realistic CMB distorted spectra at various cosmic epochs. For reasonable MF strengths we found that the CE contribution to the evolution of the CMB spectrum is much smaller than the BR and DC contributions. The constraints on the energy exchanges at various redshifts can be then derived, under quite general assumptions, by considering only Compton scattering (CS), BR, and DC, other than the considered dissipation process. Upper limits to the CMB polarization degree induced by CE have been estimated.

Key words: cosmic microwave background – magnetic fields – radiation mechanism: non-thermal

1. Introduction

The CMB spectrum emerged from the thermalization redshift, \( z_{\text{therm}} \), with a shape very close to a blackbody (BB) one, owing to the tight coupling between radiation and matter through CS and photon production/absorption processes, DC and BR. In the presence of a cosmic MF, another photon production-absorption process, CE, operates in the cosmic plasma (Puy & Peter 1998). Since the very large electron conductivity the magnetic flux through any loop moving with fluid is a conserved quantity. On scale where diffusion can be neglected the field is said to be frozen-in, in the sense that lines of force move together with the fluid. Assuming that the Universe expands isotropically, magnetic flux conservation implies \( B(t) = B(t_0) \left( \frac{a(t)}{a(t_0)} \right)^2 = B_0(1+z)^2 \), \( B_0 \) being the MF at the present time. Considering the cyclotron spontaneous emission, absorption and stimulated emission terms (Afshordi 2002), we derived the CE contribution to the evolution of the CMB photon occupation number, \( \eta \), as a further term in the Kompaneets equation (Zizzo & Burigana 2005):

\[
\frac{\partial \eta}{\partial t} = \frac{1}{\phi} \frac{1}{c^2} \int \frac{1}{x^2} \left[ \frac{\partial \eta}{\partial x} + \eta(1+\eta) \right] \frac{df}{dx_e},
\]

\[
\frac{1}{x^2} \left[ K_{\text{BR}} \frac{g_{\text{BR}}}{x_e^4} e^{-x_e} + K_{\text{DC}} \frac{g_{\text{DC}}}{x_e^3} + K_{\text{CE}} \delta(x_e - x_{e,\text{CE}}) \right]
\]

\[
\cdot [1 - \eta(e^{x_e} - 1)];
\]

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here the BR and DC rates are defined by the coefficients \( K(z) \) and the Gaunt factors, \( g_{\text{BR}} \) and \( g_{\text{DC}} \), \( t_C = mc^2/|kT_e(n_e\sigma_T)| \) is the timescale for the achievement of kinetic equilibrium between radiation and matter, \( \phi = T_e/T_r \) where \( T_r = T_0(1+z) \) is the CMB temperature and \( T_e \) the electron one, \( x = \phi x_e \) (see, e.g., Burigana, De Zotti & Danese 1995 and references therein), \( x_{e,\text{CE}} = x_{e,\text{abs}} \approx 4.97 \times 10^{-5} \cdot \phi^{-1} \left( \frac{T_0}{50\text{K}} \right)^{-1} B_0 (1+z) \) is the dimensionless frequency of CE, and \( K_{\text{CE}}(z) = \frac{4\pi^2 e^2}{3g_{\text{BR}}(z)} \) \( n_e = 4.64 \times 10^{-4} \hat{\Omega}_b \cdot B^{-1}(z)(1+z)^3 \text{s}^{-1} \) where \( \hat{\Omega}_b = \Omega_b H_0/(50\text{Kms}^{-1}\text{Mpc}^{-1})^2 \), \( \Omega_b \) being the baryon density parameter and \( H_0 \) the Hubble constant.

In Fig. 1 we compare \( x_{e,\text{CE}} \) with the frequency \( x_{e,c} \), at which the combined DC and BR absorption time \( t_{\text{abs}} \) is equal to \( t_C \) and the maximum frequency \( x_{e,\text{abs}} \), at which DC and BR could re-establish a BB spectrum after a distortion.

2. Results

We applied the above formalism for realistic assumptions of \( \eta \) to compute the global photon production rate as a function of the relevant parameters and understand the role of the CE in the thermalization and evolution of the CMB spectrum. We computed the photon number and photon energy production rates. The contributions by BR, DC, and CE for an energy dissipation occurring at high \( z \) by assuming for \( \eta \) a pure Bose-Einstein (BE) formula with a constant chemical poten-
2 RESULTS

Fig. 1. Comparison between the characteristic frequencies $x_{e,c}$ (thick solid line) $x_{e,abs}$ (thin solid line), and $x_{e,CE}$ for different values of the MF $B_0$: $10^{-9}$G (thick dashed line), $10^{-8}$G (thick dot-dashed line), $10^{-7}$G (thick three dots and dash line). Different values of the fractional energy $\Delta \varepsilon / \varepsilon_i$ ($\approx \mu_0/1.4$ for $\mu_0 \ll 1$), injected in the CMB radiation field in the case of early (BE-like) distorted spectra, have been assumed in the panels: $10^{-4}$ (panel a), $10^{-2}$ (panel b), 1 (panel c). The cosmological parameters have been assumed in agreement with WMAP (see Tab. 3 of Bennett et al. 2003); nevertheless the detailed choice of them is not critical here.

Fig. 2. Photon number injection fractional (i.e. divided by the photon number density of a BB at temperature $T_0(1+z)$) rates at the redshift $z$ from DC (dots), BR (long dashes) and CE (dashes): $B_0 = 2 \times 10^{-6}$ G; dots-dashes: $B_0 = 2 \times 10^{-5}$ G; three dots-dashes: $B_0 = 2 \times 10^{-4}$ G) in the presence of an early distortion with $\mu_0 = 1.4 \times 10^{-2}$ (top panels) or 1.4 (bottom panels) occurring exactly at the redshift $z$ (properly speaking this result holds for $z \gtrsim z_1$ while it is only indicative for $z \lesssim z_1$). In panels a and b the appropriate BE-like spectrum ($\mu = \mu(x_e)$) is assumed. In panels a1 and b1 the simplistic case $\mu = \mu_0$ is considered. Panels a2 and b2 are identical to panels a1 and b1 but for $B_0 = 10^{-9}$ G (dashes), $B_0 = 10^{-8}$ G (dots-dashes), $B_0 = 10^{-7}$ G (three dots-dashes): the simplistic assumption $\mu = \mu_0$ would imply the (wrong) conclusion of a dominance of the CE contribution for reasonable values of the MF. (Note that the DC and BR rates in panels a1, b1, a2, and b2 are only indicative because of the integral low frequency divergency in the case of a frequency independent chemical potential. We corrected here an erroneous multiplicative factor 2 included in all the rates plotted in Figs. 2 and 3 of Zizzo & Burigana (2005) because of a typo only in the corresponding IDL visualization procedure).

We derived also upper limits to the CMB polarization degree induced by the CE process. The corresponding signal turns to be much more smaller than the signal of CMB polarization anisotropies and of that predicted for the CMB polarization anisotropies “directly” induced by cosmic MFs (Subramanian et al. 2003), and is below observational chances.

For many models of dissipation mechanisms, as in the case of dissipation processes mediated by energy exchanges between matter and radiation or associated to photon injections at $\nu$ significantly different from $\nu_c$, the role of CE in the evolution of CMB spectral distortions is negligible for cosmic MF realistic values. In particular, it cannot re-establish a BB spectrum after the generation of early distortions and it cannot significantly distort the CMB spectrum. No significant limits on the cosmic MF strength can be then set by constraints on CMB spectral distortions when interpreted as produced by CE. Consequently, energy dissipation processes can be studied by considering only CS, BR, and DC, other than, obviously, the considered mechanism(s).
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