Astroparticle Physics 70 (2015) 27–32

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Non-thermal shielding effects on the Compton scattering power in astrophysical plasmas

Dong-Soo Shin [a,b], Young-Dae Jung [a,b,c,*]

[a] Department of Applied Physics, Hanyang University, Ansan, Kyunggi-Do 426-791, South Korea
[b] Department of Bionanotechnology, Hanyang University, Ansan, Kyunggi-Do 426-791, South Korea
[c] Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180-3590, USA

ARTICLE INFO

Article history:
Received 7 January 2015
Received in revised form 25 February 2015
Accepted 16 March 2015
Available online 16 April 2015

Keywords:
Atomic processes
Compton scattering
Astrophysical plasmas

ABSTRACT

The non-thermal shielding effects on the inverse Compton scattering are investigated in astrophysical non-thermal Lorentzian plasmas. The inverse Compton power is obtained by the modified Compton scattering cross section in Lorentzian plasmas with the blackbody photon distribution. The total Compton power is also obtained by the Lorentzan distribution of plasmas. It is found that the influence of non-thermal character of the plasma suppresses the inverse Compton power in astrophysical Lorentzian plasmas. It is also found that the non-thermal effect on the inverse Compton power decreases with an increase of the temperature. In addition, the non-thermal effect on the total Compton power with Lorentzan plasmas increases in low-temperature photons and, however, decreases in intermediate-temperature photons with increasing Debye length. The variation of the total Compton power is also discussed.

1. Introduction

The absorption and scattering of electromagnetic radiation in astrophysical plasmas are tremendously important since these processes provide useful information on the physical nature of the electromagnetic radiation as well as the density correlation and fluctuations of the plasma [1–5]. It is known that the scattered photon energy is smaller than the incident photon energy due to the recoil of the electron in the Compton scattering process of electromagnetic radiation from free electrons for low-photon energies [4]. In the inverse Compton scattering, net energy would be transferred from the electron to the photon when the kinetic energy of the moving electron is greater than the energy of the photon [3,6]. Hence, the inverse Compton power in plasmas has been used as the plasma diagnostic tool since the spectrum of scattered radiation provides the physical information on the photon distribution as well as the surrounding plasma particle [7]. In addition, the inverse Compton process has received a considerable attention in astrophysics since this process generates X-rays by the scattering of high-energy electrons in the interstellar medium with photons in the cosmic microwave background which is known as the Sunyaev–Zeldovich effect [8]. In ideal or weakly coupled classical plasmas, the screened interaction potential has been described by the Debye–Hückel model since the average interaction energy between plasma particles is usually smaller than the average kinetic energy of a plasma particle. Hence, the atomic collision and radiation physical processes in Maxwellian plasmas have been extensively explored by using the usual Debye–Hückel interaction potential [4,9]. The inverse Compton power has been extensively investigated with the Maxwellian distribution in thermal equilibrium [10]. However, the inverse Compton power in astrophysical Lorentzian plasmas with the blackbody photon distribution has not been investigated as yet even though the coupling of the external field with equilibrium plasmas often generates asymmetric non-thermal electrons fit very well by the Lorentzian distribution function [11–20]. Then, it would be expected that the inverse Compton powers in astrophysical Lorentzian plasmas is quite different from those in Maxwellian plasmas due to the non-thermal character of the astrophysical Lorentzian plasma. Hence, in this paper, we investigate the influence of non-thermal shielding character on the inverse Compton power by the scattering of electromagnetic radiation with the blackbody distribution with the astrophysical Lorentzian plasma. The inverse Compton power is obtained by the modified Compton scattering cross section including the static structure factor derived by the fluctuation–dissipation theorem in astrophysical Lorentzian plasmas with the blackbody photon distribution. In addition, the total Compton power is obtained as a function of the spectral index and plasma

* Corresponding author at: Department of Applied Physics, Hanyang University, Ansan, Kyunggi-Do 426-791, South Korea. Tel.: +82 31 400 5477; fax: +82 31 400 5457.

E-mail address: ydjung@hanyang.ac.kr (Y.-D. Jung).

http://dx.doi.org/10.1016/j.astropartphys.2015.03.012

parameters of the Lorentzian distribution. The variations of the influence of non-thermal character on the total Compton power in astrophysical Lorentzian plasmas are also discussed.

In Section 2, we discuss the distribution and plasma dielectric function in astrophysical Lorentzian plasmas. In Section 3, we obtain the analytic expression of the total Compton scattering cross section including the non-thermal effects of Lorentzian plasmas. In Section 4, we obtain the inverse Compton power (energy per unit time) and the total Compton power (energy per unit volume, per unit time) by the scattering of blackbody photon with astrophysical Lorentzian plasmas. In Section 5, we discuss the influence of non-thermal character of plasmas on the Compton power in Lorentzian plasmas. Finally, the conclusions are given in Section 6.

2. Distribution and plasma dielectric function in Lorentzian plasmas

It has been shown that the external disturbances in astrophysical and laboratory thermal plasmas frequently generate the high-energy tail of plasma electrons deviated from the equilibrium Maxwellian distribution [11]. In addition, it is shown that the asymmetric plasma distribution function due to the high-energy portion of these non-thermal plasmas can be modeled practically by the generalized Lorentzian velocity distribution [11,14] $f_{Lorentz}(\kappa, v)$ known as

$$f_{Lorentz}(\kappa, v) = n\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)}\left(\frac{m}{2\pi\kappa E_\kappa}\right)^{3/2}\left(1+\frac{mv^2}{2\kappa E_\kappa}\right)^{-(\kappa+1)}, \tag{1}$$

with the normalization: $\int d^3\boldsymbol{v} f_{Lorentz}(\kappa, v) = n$, where n is the number density of plasma electrons in the astrophysical system, the parameter $\kappa(>1/2)$ is the spectral index of the Lorentzian plasma, v is the velocity of the plasma electron, $\Gamma(z)$ represents the Gamma function with the argument z, m is the mass of the electron, $E_\kappa[\equiv(\kappa-3/2)E_T/\kappa]$ is the characteristic energy in Lorentzian plasmas, $E_T \equiv k_B T, k_B$ is the Boltzmann constant, and T is the plasma temperature. It is interesting to note that the non-thermal Lorentzian velocity distribution $f_{Lorentz}(\kappa, v)$ encompasses several important physical characteristics. The Lorentzian distribution function $f_{Lorentz}(\kappa, v)$ yields a simple inverse power-law form [11] at high velocities, i.e., $mv^2 >> 2\kappa E_\kappa$, such as $f_{Lorentz}(\kappa, v) \propto (mv^2/2\kappa E_\kappa)^{-(\kappa+1)}$. In addition, the Lorentzian distribution becomes the Maxwellian form [17] in the limit of $\kappa\to\infty$ such as $f_{Lorentz}(\kappa\to\infty, v) \propto \exp(-mv^2/2E_{\kappa\to\infty})$, where $E_{\kappa\to\infty}\to k_B T(=E_T)$ corresponds to the characteristic energy in thermal plasmas. Moreover, the effective screening distance [17], i.e., the critical correlation length, λ_κ in non-thermal astrophysical Lorentzian plasmas has been obtained by $\lambda_\kappa = \sqrt{(\kappa-3/2)/(\kappa-1/2)}\lambda_D$, where the factor $\sqrt{(\kappa-3/2)/(\kappa-1/2)}$ is known as the characteristic non-thermal factor which stands for the measure of the fraction of the high-velocity population in the non-thermal Lorenzian plasmas and λ_D is the usual Debye distance in Maxwellian plasmas. Based on the plasma kinetic theory, the plasma dielectric function [13] $\varepsilon_{Lorentz}(\mathbf{q}, \omega)$ in astrophysical Lorentzian electron plasmas would be represented by

$$\varepsilon_{Lorentz}(\mathbf{q}, \omega) = 1+\frac{1}{q^2\lambda_\kappa^2}\left(\frac{\kappa}{\kappa-3/2}\right)\left[\left(\frac{\kappa-1/2}{\kappa}\right)+\xi Z_\kappa(\xi)\right], \tag{2}$$

where $\mathbf{q}$ is the wave number, ω is the frequency, q is the wave number, $\xi\equiv(\omega/k)(2E_\kappa/m)^{-1/2}$, and $Z_\kappa(\xi)$ is the modified plasma dispersion function in Lorentzian distribution plasmas:

$$Z_\kappa(\xi) = \frac{1}{\pi^{1/2}\kappa^{3/2}}\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)}\int_{-\infty}^{\infty}\frac{dz}{(z-\xi)(1+z^2/\kappa)^{\kappa+1}}. \tag{3}$$

The derivation of the Compton scattering cross section in astrophysical non-thermal Lorentzain plasmas will be discussed in the following section.

3. Total Compton scattering cross section in Lorentzian plasmas

In non-relativistic cases, the differential Compton scattering cross section [21–25] $d\sigma_C$ of the plasma electrons by the electromagnetic radiation would be represented by the integration over the frequency ω and also by the average over the initial polarization directions $\hat{\varepsilon}_i$ and summation over the final polarization directions $\hat{\varepsilon}_f$:

$$d\sigma_C = N\left(\frac{e^2}{mc^2}\right)^2\left(1-\frac{1}{2}\sin^2\Theta\right)d\Omega S_{SF}(\mathbf{k}_i, \mathbf{k}_f), \tag{4}$$

where N is the number of plasma electrons in the system of volume V, e is the charge of the electron, $\hat{\varepsilon}_i$ and $\hat{\varepsilon}_f$ are unit polarization vectors for the incident and scattered waves, Θ is the angle between the incident wave vector $\mathbf{k}_i$ and scattered wave vector $\mathbf{k}_f$, and $d\Omega$ is the differential solid angle, respectively. Here, $S_{SF}(\mathbf{k}_i, \mathbf{k}_f)$ is the static structure factor determined by the Wiener–Khinchine theorem [22] with the correlation function $\rho_q(t)$, i.e., the spatial Fourier component of the electron-density function $\rho(\mathbf{r}, t)$ at the position $\mathbf{r}$ and time t:

$$\begin{aligned} S_{SF}(\mathbf{q}) &= \frac{1}{2\pi n}\int_{-\infty}^{\infty}d\omega\int_{-\infty}^{\infty}dt\left\langle\rho_{\mathbf{q}}(t'+t)\rho_{-\mathbf{q}}(t')\right\rangle e^{i\omega t} \\ &= \frac{1}{n}\left\langle\left|\rho_{\mathbf{q}}(t)\right|^2\right\rangle, \end{aligned} \tag{5}$$

where $\mathbf{q}\equiv\mathbf{k}_f-\mathbf{k}_i$, and the bracket notation $\langle\ \rangle$ represents the mean square average. Using the plasma dielectric function $\varepsilon_{Lorentz}(\mathbf{q}, \omega)$ (Eq. (2)) in low-frequency limit and the fluctuation–dissipation theorem [21], the structure factor [23] $S_{Lorentz}(k, \kappa)$ in astrophysical non-thermal Lorentzian plasmas is then obtained by

$$S_{Lorentz}(k, \kappa) = k^2\lambda_D^2\left(\frac{2\kappa-3}{2\kappa-1}\right)\Big/\left[1+k^2\lambda_D^2\left(\frac{2\kappa-3}{2\kappa-1}\right)\right], \tag{6}$$

when $\hbar\omega/mc^2 << 1$, where $|\mathbf{k}_i|\approx|\mathbf{k}_f| = k$ and $\hbar$ is the rationalized Planck constant. From $S_{Lorentz}(k, \kappa)$, we have found that the electrostatic interaction would be negligible in short-wavelength regions ($k\lambda_D >> 1$) and, however, the electrostatic coupling is quite strong in long-wavelength regions ($k\lambda_D << 1$) in astrophysical non-thermal Lorentzian plasmas except when $\kappa >> 3/2$. In strong non-thermal domains such as $\kappa\approx 3/2$, the electrostatic interaction in astrophysical Lorentzian plasmas can also be strong enough even in short-wavelength regions. The detailed discussions on the fluctuation–dissipation theorem can be fund in a recent volume by Peliti [26]. If we take the limit of $\kappa\to\infty$ in the Lorentzian structure factor $S_{Lorentz}(\mathbf{k})$ (Eq. (6)), the structure factor is found to be $S_{Lorentz}(\mathbf{k}, \kappa\to\infty) = k^2\lambda_D^2/(1+k^2\lambda_D^2)$, which is the case of the Maxwellian structure factor [27] $S_{Maxwell}(\mathbf{k})$ in thermal plasmas. Hence, the differential Compton scattering cross section [23] per unit solid angle when $\hbar\omega/mc^2 << 1$ by the electromagnetic radiation in astrophysical Lorentzian plasmas including the influence of non-thermal shielding is given by

$$\begin{aligned} \left(\frac{d\sigma_C}{d\Omega}\right)_{Lorentz} &= 2\pi N r_0^2 \\ &\times\frac{2k^2\lambda_D^2(1-\cos\Theta)\left(\frac{\kappa-3/2}{\kappa-1/2}\right)}{1+2k^2\lambda_D^2(1-\cos\Theta)\left(\frac{\kappa-3/2}{\kappa-1/2}\right)}\left(1-\frac{1}{2}\sin^2\Theta\right), \end{aligned} \tag{7}$$