CASCADE PROCESSES IN THE SURFACE LAYERS OF PULSARS

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Abstract. The influence of the Landau–Pomeranchuk effect on the development of a shower generated by ultrarelativistic particles bombarding the surface of a pulsar is discussed. Because of this effect, the path length of the shower increases while low-energy photon generation is strongly suppressed. In view of this, the mechanism of pair production suggested by Cheng, Ruderman, and Jones for the pulsar magnetosphere, may be essential only for pulsars whose magnetic field intensity at the surface lies in a relatively narrow range of around \( B \approx 10^{12} \) G.

1. Introduction

Electrons and positrons created in the polar gap of a pulsar are accelerated in opposite directions up to energies of \( \sim 10^3 \) GeV (Ruderman and Sutherland, 1975; Arons, 1981). Ultra-relativistic particles (electrons in Ruderman and Sutherland’s model or positrons in Arons’s model) move along the magnetic field lines to the pulsar surface and form showers by crossing it. This paper considers the properties of these showers and discusses the question of electron-positron pair formation in the polar gap of a pulsar due to the \( \gamma \)-quanta absorption in the magnetic field, generated in a developing shower and moving back to the pulsar magnetosphere at sufficiently large angles to the magnetic field direction.

2. Electromagnetic Showers in Superdense Matter

The passage of electrons and photons of relatively low energies \( (E_0 \lesssim 10^{12} \) eV through matter with a density of \( \rho \lesssim 10 \) g cm\(^{-3}\) is well described by the equations of the electromagnetic cascade theory with Bethe–Heitler cross-sections (Belen’ky, 1948). In condensed material, the Bethe–Heitler theory for bremsstrahlung radiation and pair formation on isolated atoms becomes inapplicable from \( E_0 > 10^{12} \) to \( 10^{13} \) eV. This is so since, at sufficiently large energies \( E \) of shower particles in the dense matter, the probability of photon generation (especially low-energy photons \( E_\gamma \ll E \)) and their conversion into \( e^+, e^- \) pairs, decreases with an increasing formation zone of cascade processes (Landau and Pomeranchuk, 1953). The higher the matter density, the stronger the suppression of bremsstrahlung radiation and pair formation because of the Landau–Pomeranchuk effect.

The density of matter that is composed of atoms with a nuclear charge \( Z e \) in a magnetic field \( B \sim 10^{12}–10^{13} \) G, which is typical of pulsars, is given by Flowers et al. (1977)

\[
\rho = 4.4 \times 10^3 \left( \frac{Z}{26} \right)^{-3/5} \left( \frac{B}{10^{12} \text{ G}} \right)^{6/5} \text{ g cm}^{-3}.
\]
As will be shown below (see (10) and (11)) the Landau–Pomeranchuk effect strongly influences the radiation processes if $\gamma \chi \gtrsim 3 \times 10^8$, where $\gamma = E/mc^2$ is the particle Lorentz factor, $\chi = \rho/\rho_0$ ($\rho_0$ is the density of condensed matter in normal conditions, when $B = 0$).

Most probably, the surface layers of pulsars mainly consist of iron ($Z = 26$, $\rho_0 = 7.8 \text{ g cm}^{-3}$), for which

$$\chi = 5.6 \times 10^2 \left(\frac{B}{10^{12} \text{ G}}\right)^{6/5}. \quad (2)$$

For primary particles with $\gamma \approx (2-3) \times 10^6$ bombarding the pulsar surface with $B \gtrsim 10^{12} \text{ G}$, we have $\gamma \chi > 3 \times 10^8$ and, therefore, the Landau–Pomeranchuk effect should be taken into account at the initial stage of shower development.

The probabilities of bremsstrahlung radiation and pair formation, normalized to t-unit and with the multiple-scattering effect taken into account are written (cf. Migdal, 1956, 1957) as

$$w_r \, dv = \xi(s) \left\{ v^2 G(s) + 2[1 + (1 - v^2)] \Phi(s) \right\} \frac{dv}{3v}, \quad (3)$$

$$w_p \, du = \xi(s) \left\{ G(s) + 2[u^2 + (1 - u)^2] \Phi(s) \right\} \frac{du}{3}, \quad (4)$$

where $v = E_\gamma/E_e$ (here $E_e$ and $E_\gamma$ are the energies of the emitted electron and photon), $u = E_e/E_\gamma$ ($E_\gamma$ is the energy of a photon creating a pair and $E_e$ is the energy of one of the components in this pair)

$$G(s) = 48s^3 \left[ \frac{\pi}{4} - \frac{1}{2} \int_0^\infty e^{-sx} \frac{\sin sx}{\sinh sx} \, dx \right], \quad (5)$$

$$\Phi(s) = 12s^2 \int_0^\infty \coth \left( \frac{x}{2} \right) e^{-sx} \sin sx \, dx - 6\pi s^2, \quad (6)$$

$$\xi(s) = \begin{cases} 
1, & s > 1, \\
1 + [\ln(1/s_1)]^{-1} \ln(1/s), & s_1 < s < 1, \\
2, & s < s_1,
\end{cases} \quad (7)$$

$$s_1 = \left[ 22Z^{1/5} \left( \frac{B}{10^{12} \text{ G}} \right)^{-2/5} \right]^{-2}, \quad (8)$$

$$s = 1.4 \times 10^3 \left[ \frac{\nu t_0}{\sqrt{\gamma \chi \xi (1 - v)}} \right]^{1/2}, \quad \bar{s} = 1.4 \times 10^3 \left[ \frac{t_0}{\gamma \chi \xi u (1 - u)} \right]^{1/2}, \quad (9)$$

$t_0$ is the radiation length at $\chi = 1$ (in cm) (for iron $t_0 \approx 1.7 \text{ cm}$), $\bar{\gamma} = E_\gamma/mc^2$. 