PHOTON CAPTURE IN PULSAR MAGNETIC FIELDS

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Abstract. We investigate the process of photon capture by strong magnetic fields, by transforming it into a positronium, and the subsequent decay of the positronium into two photons. We discuss the implications of this process for the polar gap models of pulsars. We find that the capture process is energy-dependent and photons above a certain energy (depending on the magnetic field) are not captured and can decay into electron-positron pairs. This leads to increased gap heights in the model and leads to higher luminosities than found earlier. We also find that it may be possible for very high-energy positronia to escape the magnetosphere of the pulsar and be observed near the Earth as photons in agreement with the recent observations of $10^{12}$ eV gamma-rays from some pulsars.

1. Introduction

Pulsars discovered almost two decades ago, have turned out to be precise clocks which can be used to check theories of emission of gravitational radiation as well as to detect long wavelength gravitational radiation. The nature and the origin of the pulsed radiation at various wavelengths is, however, poorly understood till now. Pulsars are generally believed to be neutron stars with very strong magnetic fields ($\sim 10^{12}$ G) in which the particle motions are dominated by electromagnetic fields rather than the surface gravity. The few models that have been proposed for the emission of the pulsed radiation depend crucially on the production of electron-positron pairs by high-energy photons (produced by curvature radiation) in strong magnetic fields. Recently, it has been noted (Herold et al., 1985; Shabad and Usov, 1982, 1986) that when the magnetic fields become very high ($> 0.1 B_c, B_c = m^2/e \approx 4.4 \times 10^{13}$ G in units in which $\hbar = c = 1$ and where $m$ and $e$ are the mass and charge of the electron), it is possible for the high-energy photons to get converted into the bound electron-positron systems which keep moving along the magnetic field lines. The consequent suppression of the pair creation process is expected to have important bearing on the pulsar emission mechanisms.

In this paper we discuss the photon capture process in strong magnetic fields and its consequence for the polar gap models suggested principally by Ruderman and Sutherland (1975) (referred in what follows as the RS theory). In these models the emission region is thought to be near the poles, close to the surface of the star. The region is charge-free and there is a very large potential drop ($\sim 10^{12}$ V) across it. The charged particles are accelerated in this region, or gap, to very high energies and emit $\gamma$-rays by curvature radiation. These $\gamma$-rays break into electron-positron pairs, which serve to terminate the gap. A total suppression of pair creation by photons would seriously upset this model. However, we find that the suppression is not valid above a certain energy. This results in the increase of the gap height and thereby of the total luminosity of the pulsar which is proportional to the square of the gap height.

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It is generally believed that the photons emitted close to the stellar surface cannot escape the magnetosphere of the pulsar because of the pair creation induced by the strong magnetic field. However, if we take into account the capture of photons in strong magnetic fields, we see the possibility of a fraction of very high-energy photons escaping the pulsar magnetosphere. We suggest that these escaped photons may explain the observed $10^3$ GeV $\gamma$-rays from pulsars such as the Crab and Vela (Bhat et al., 1980; Dowthaite et al., 1984).

In Section 2 we discuss the capture of photons in strong magnetic fields by conversion into positronia. In Section 3 we derive an equation for the length of the vacuum gap when the photon capture is significant. In Section 4 we investigate the decay of the converted positronia and the possible source of the high-energy pulsed $\gamma$-rays. In Section 5 we summarize our conclusions.

2. Conversion of Photons to Pairs

In free space a single photon cannot decay into an electron–positron pair. This constraint, which is due to the conservation of energy and momentum, does not apply when a magnetic field is present. In a uniform magnetic field the conserved generalised momentum includes terms like $eB \times r$. If the magnetic field is along the $z$-axis, the generalised momentum conservation takes the form

$$k = eB(y^- - y^+) = (p^+_x + p^-_x),$$

where $k_\perp$ is the photon momentum perpendicular to the magnetic field (see Shabad and Usov, 1986) and $y^-$ and $y^+$ are the $y$-coordinates of the centres of the Landau orbits of $e^-$ and $e^+$, respectively. Equation (1) which is valid for a free pair can also be applied to a bound pair or positronium if the Coulomb interaction can be treated as a perturbation. This is possible when the Landau radius for the electron (or positron) is smaller than the Bohr radius of the bound pair and is the case when $B > 2 \times 10^9$ G. The binding energy of the positronium is a function of the photon momentum $k_\perp$ (equivalently, the separation of the orbit centres of $e^-$ and $e^+$). The binding energy for $k_\perp = 0$ (when $B = 4.7 \times 10^{12}$ G) is 150 eV. For $k_\perp = 2m$, the point at which the photon reaches the threshold for pair creation, it falls to about 67 eV (Herold et al., 1985).

The bound pair or positronium and the photon can have the same quantum numbers. While the energy of the photon is $k (\text{in the frame in which } k_{\parallel} = 0)$ the energy of the positronium depends very mildly on $k_\perp$ (Figure 1). The energy levels of the two systems cross at $k_\perp \approx 2m$. The degeneracy of the two systems at this point is lifted by their interaction (vacuum polarisation correction) and leads to two modified energy levels with an energy gap. The value of the gap is given (cf. Shabad and Usov, 1982, 1986; Herold et al., 1985) by

$$\Delta k = \omega n [2 \ln (B/2x B_c)]^{1/2} (B/B_c)^{1/2} e^{-B_{c}/B},$$

$$\approx 10^{-1} \text{ eV at } B = B_c/10,$$

(2)