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RADIATIVE OPACITIES AND COMPTON SCATTERING IN STRONG MAGNETIC FIELDS

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ABSTRACT

The Compton radiative opacity is computed in the presence of a strong magnetic field. It is found that the opacity along the magnetic field is decreased by a factor of $(\omega/\omega_H)^2$, where ω_H is the cyclotron frequency, for both kinds of circular polarization. For the transverse opacity, half of the intensity is strongly absorbed when the electric field of the wave is parallel to H, while for the other half the opacity is reduced by the same factor of $(\omega/\omega_H)^2$.

I. INTRODUCTION

It is now well established that the radiation from pulsars has to be of strongly nonthermal origin. Any theory that attempts to explain such an unusual phenomenon has to propose a mechanism to upset the thermodynamic equilibrium of the electron gas; i.e., a maserlike action has to occur. The choice of a specific electromagnetic process through which the electrons emit the radiation is, in itself, of no decisive importance in the sense that it is relatively easy to find "ordinary" electromagnetic processes which will satisfy the conditions to be met in order to have a maser action or, equivalently, a negative absorption coefficient (Chiu and Canuto 1970*a*, *b*). By ordinary electromagnetic processes we mean, for instance, synchrotron radiation or bremsstrahlung, to cite the most familiar. A nonequilibrium electron distribution function can have a variety of different forms, the most commonly used being a δ-function type (Bekefi 1966) or a modified Maxwell distribution of the form (Hirshfield and Bekefi 1963)

$$f(p) = p^{\alpha} \exp(-\beta p^2) , \qquad \beta^{-1} = 2mkT , \quad (1)$$

where α is a parameter. Such a distribution has a positive derivative for certain values of the parameter α.

Once the radiation is emitted, the degree of beaming is essentially due to the variety of possible processes which make up the opacity of the medium. In this paper we intend to show how the magnetic field drastically influences the opacity of the medium. Of the various possible mechanisms giving rise to opacity we will be concerned only with the Compton (or, more properly, Thomson) scattering. The problem of Compton scattering in a magnetic field has been dealt with quantum mechanically for propagation parallel and perpendicular to the magnetic field and classically for propagation at intermediate angles. By classically it is meant that one first solves the equation of motion of an electron under the combined influence of a magnetic field and the electric field of a plane wave. Once the intensity of $I(\omega)$ of the emitted radiation is computed, the Compton cross-section is simply obtained by dividing $I(\omega)$ by the Poynting vector.

The wave function of a nonrelativistic electron in a magnetic field (Canuto and Chiu 1968*a*, *b*, *c*) has been used to compute the Compton cross-section by the standard

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method. A detailed derivation of the results will be given elsewhere (Canuto 1970). We report here the result of such a computation.

II. LONGITUDINAL PROPAGATION, $\theta = 0$[1]

Along the magnetic field only two kinds of waves can propagate: (*a*) a right-hand circularly polarized extraordinary wave, X, with a cross-section given by

$$\left(\frac{d\sigma}{d\Omega}\right)_X = \tfrac{1}{2}r_0^2 \frac{\omega^2}{(\omega - \omega_H)^2} \simeq \tfrac{1}{2}r_0^2\left(\frac{\omega}{\omega_H}\right)^2, \qquad \omega \ll \omega_H = \frac{eH}{mc}, \tag{2}$$

and (*b*) a left-hand circularly polarized ordinary wave (0), with a cross-section given by

$$\left(\frac{d\sigma}{d\Omega}\right) = \tfrac{1}{2}r_0^2 \frac{\omega^2}{(\omega + \omega_H)^2} \simeq \tfrac{1}{2}r_0^2\left(\frac{\omega}{\omega_H}\right)^2. \tag{3}$$

Both waves have a much lower cross-section with respect to the free case in the ratio $(\omega/\omega_H)^2$. This results in a corresponding lowering of the opacity K_H with respect to the one without the magnetic field in the ratio $(\omega/\omega_H)^2 \simeq 10^2$, as we will see later. One therefore concludes that along the lines of the magnetic field a photon can easily stream out without interaction with the surroundings.

III. TRANSVERSE PROPAGATION, $\theta = \frac{1}{2}\pi$

As before, one has to distinguish two cases. When the photon travels at 90° but its electric vector is parallel to the magnetic field, the cross-section is maximum since there is a strong interaction between $\boldsymbol{E}$ and the free motion of the electrons in the z-direction. The result is

$$\left(\frac{d\sigma}{d\Omega}\right)_{E\parallel H} = \tfrac{1}{2}r_0^2 \qquad \text{(ordinary wave)}\ ; \tag{4}$$

i.e., the magnetic field has no effect on it and therefore it is strongly absorbed.

If, however, the electric field of the wave is perpendicular to H, then the differential cross-section turns out to be

$$\left(\frac{d\sigma}{d\Omega}\right)_{E\perp H} = \tfrac{1}{2}r_0^2 \frac{\omega^2}{(\omega - \omega_H)^2} \simeq \tfrac{1}{2}r_0^2\left(\frac{\omega}{\omega_H}\right)^2 \qquad \text{(extraordinary wave)}\ . \tag{5}$$

This cross-section is lowered by a factor $(\omega/\omega_H)^2$ with respect to the other half of the wave; i.e., the wave can stream out very easily since the opacity is correspondingly reduced by a factor of $(\omega/\omega_H)^2$.

To recapitulate, we see that the effect of the magnetic field on Compton scattering is to reduce the opacity for both kinds of polarizations for longitudinal propagation; i.e.,

$$(K_0/K_H)_{\theta=0} = 1 + \tfrac{5}{4}x^2 \pm 5.48x\ , \tag{6}$$

where

$$x = \frac{H/Hq}{kT/mc^2} \geq 10\ , \qquad Hq = 4.4 \times 10^{13}\ \text{gauss}\ , \qquad K_0 = \frac{4\pi r_0^2 Z}{m_{\mathrm{H}} A}\ . \tag{7}$$

This result was obtained by averaging the cross-section over the frequencies as dictated by the Rosseland mean.

On the other hand, for transverse propagation, half of the intensity of the wave is strongly absorbed, i.e.,

$$(K_0/K_H)_{E\parallel H} \simeq 1\ ; \tag{8}$$

[1] Similar results have been obtained by J. Lodenquai and M. Ruderman (private communication, 1970).

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whereas for the other half the opacity is reduced by the factor

$$(K_0/K_H)_{E\perp H} \simeq x^2 . \tag{9}$$

When ion motion is taken into account, plasma effects do not alter this general consideration. The only wave which would be strongly affected by the effect of plasma is at $\theta = \frac{1}{2}\pi$ when E is parallel to H, for which $n^2 < 0$ in the radio region.

For $H \simeq 10^{12}$ gauss, $T \simeq 10^7$ ° K, $x \simeq 15$ and therefore the opacity along the magnetic field and for one of the possible polarizations at $\frac{1}{2}\pi$ is decreased by the greater amount of 10^2.

One therefore concludes that the Compton effect has a strong influence on the beaming of the radiation and that the loci of minimum radiative opacity are parallel and perpendicular (special type of polarization) to the magnetic-field lines where the photon mean free path is increased by a factor of about 10^2 by the presence of the magnetic field. The influence of the magnetic field on the cooling time of a neutron star (Chiu and Salpeter 1964) is under study.

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