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Abstract

Full Text

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PHYSICS

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ON A NEW MECHANISM FOR THE GENERATION OF RELATIVISTIC ELECTRONS IN COSMIC SPACE

The purpose of the present note is to point out the existence of one very simple and general mechanism for the generation of fast electrons, which until now has remained unnoticed. It seems to the author, in particular, that this mechanism may be, at least in part, the cause of that radio emission which reaches the Earth from cosmic objects and has recently been connected with the question of the origin of cosmic rays ⁽¹⁾. It will be shown below that the motion of a quasineutral clump of fully ionized plasma in an inhomogeneous magnetic field must be accompanied—provided only that certain very general conditions are satisfied—by the generation of relativistic electrons. This assertion is based essentially only on the law of conservation of energy.

The acceleration mechanism. Let us consider a spatially bounded clump of quasineutral plasma containing equal numbers of positive ions and electrons, possessing as a whole a translational velocity equal to v_0 . For clarity,* we shall restrict ourselves to the case in which the initial velocity of the clump $v_0 < c$.

Suppose that the total number of particles of each sign in the clump, N , is sufficiently large, and that the density is small. Suppose further that the dimensions of the clump a are considerably smaller than the extent of that region L within which the magnetic field changes by an appreciable amount. Under these assumptions one may regard, on the average, all N electrons and all N ions of the clump as behaving like two particles with charge and mass N times larger than the charges and masses of each ion and electron. We introduce one more simplifying assumption, which will greatly increase the clarity of the subsequent analysis. We shall assume that the inhomogeneous magnetic field has an axis of symmetry, and suppose that the quasineutral clump moves with velocity v along this axis. We introduce a cylindrical coordinate system, whose z -axis is directed along the direction of the velocity of the clump. Let us denote the radial and longitudinal components of the magnetic field into which the clump enters respectively by H_r and H_z . Let us imagine that the clump enters the

magnetic field from that region of space where the field is absent. It is obvious that when the clump enters the magnetic field, a Lorentz force F_θ , equal in magnitude for the electrons and ions of the clump (but opposite in direction), will begin to act on them, caused by the radial component of this field,

$$F_\theta = \frac{e}{c} v_z H_r.$$

This force imparts to the electrons and ions of the clump accelerations lying in a plane perpendicular to the direction of translational motion

* Everything said below will be equally valid in the relativistic region of velocities.

clump. The magnitude of the acceleration and, consequently, the magnitude of the velocities acquired by the ions and electrons under the action of this electromotive force of induction will be inversely proportional to the mass of these particles. Accordingly, the cyclic currents of ions and electrons caused by this force and by the presence of a longitudinal component of the magnetic field will differ.

In turn, the appearance of a current in a plane perpendicular to the translational velocity of the clump, in the presence of a radial component of the field, will lead to the appearance of Lorentz forces acting on the ions and electrons and directed in such a way that they will retard the translational motion of the clump as a whole.* Since the retarding force acting on the electrons is M_0/m times greater than the retarding force acting on the ions, polarization of the clump arises. The translational velocity of the electrons will decrease faster than the velocity of the ions. The centers of gravity of the electronic and ionic parts of the clump will be displaced relative to one another.

If the number of particles of both signs in the clump is sufficiently large, then the electric field of polarization will “bind” the electrons of the clump to the ions moving by inertia; the electrons will follow the ions, being in the field of the ionic skeleton of the clump, and because of this the energy of the “cyclic” motion of the electrons will continuously increase at the expense of this internal field. At the same time the electrons themselves will retard the ions. Such a process of pumping energy from the ions to the electrons will continue until the energy of the translational motion of the ions becomes practically equal to zero, i.e., until the ions stop. It is easy to show by a simple calculation that the average fraction of the energy which (when the clump is stopped) will be retained by the ions owing to the conversion of translational motion into cyclic motion will be many times smaller than the energy transferred to the electrons.

Since the polarization forces arising in the clump during braking do not allow the electrons to break away from the ions, the following equalities hold at any moment:

$$\frac{d(mv_{\theta e})}{dt} = -\frac{e}{c}v_z H r; \quad \frac{d(Mv_{\theta i})}{dt} = \frac{e}{c}v_z H r,$$

whence $v_{\theta i} = -\frac{m}{M_0}v_{\theta e}$, where $v_{\theta i}$ and $v_{\theta e}$ are the averaged velocities of the ions and electrons in the plane normal to the translational velocity of the clump as a whole. Taking the foregoing into account and regarding the ions as non-relativistic, we find that the ion energy corresponding to the indicated value of the velocity will be $W_i = \frac{M_0 v_{\theta i}^2}{2} = \frac{m^2}{2M_0}v_{\theta e}^2$, where m , in turn, is related to v_e by the well-known relativistic formula. Consequently (neglecting the radial components), the electron energy will be

$$W_e = \frac{Mv_0^2}{2} - \frac{m_0^2 \gamma^2}{2M_0}v_e^2.$$

Taking into account that $W_e = m_0 c^2(\gamma - 1)$, where

$$\gamma = \frac{1}{\sqrt{1 - v_{\theta e}^2/c^2}},$$

solving the resulting quadratic equation and neglecting terms of order m_0/M_0 and $(m_0/M_0)^2$ (where m_0 is the electron rest mass), we obtain:

$$W_e \simeq \frac{M_0 c^2}{2} \left(\sqrt{1 + \frac{2v_0^2}{c^2}} - 1 \right) \approx \frac{Mv_0^2}{2}.$$

* In the general case, besides braking, there will also be a “reflection” of the clump at some angle to the magnetic field.

Thus, on average the energy of each electron will be

$$W_e = \frac{Mv_0^2}{2} = m_0 c^2(\gamma - 1), \quad \text{i.e.} \quad \gamma = \frac{M_0}{2m_0} \frac{v_0^2}{c^2} + 1.$$

Consequently, even for a quasineutral clump consisting of electrons and hydrogen ions, for which $v_0^2/c^2 \gg 10^{-3}$, the average value of γ is considerably greater than unity, and therefore the electrons will emit specific electromagnetic radiation. The mechanism under consideration is especially effective if the heavy fraction of the clump consists of ions with large atomic weight.* Thus, for example, for mercury ions γ can (at least in principle) reach a value of 10^5 .

The case analyzed above corresponds to reflection of a quasineutral clump from a region of magnetic field at an angle of 180° and, of course, is a very special one. However, I believe that the qualitative analysis carried out shows sufficiently

convincingly a mechanism by virtue of which, in any motion of a quasineutral clump in an inhomogeneous magnetic field (apart from other processes), energy will always be transferred from the heavy fraction of the clump to the light one.

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REFERENCES

¹ V. L. Ginzburg, *Uspekhi fiz. nauk*, **51**, 343 (1953).

* Askar' yan drew my attention to the fact that an analogous process of energy transfer from the heavy fraction to the light one will also occur in the case where the light fraction in a quasineutral clump consists not of electrons but, for example, of light negative ions, while the positive ions have a mass considerably greater than that of hydrogen.

Note: Figure translations are in progress. See original paper for figures.

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