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1972 J. Phys. A: Gen. Phys. 5 L109

(http://iopscience.iop.org/0022-3689/5/10/006)

J. Phys. A: Gen. Phys., Vol. 5, October 1972. Printed in Great Britain. © 1972.

LETTER TO THE EDITOR

A photon rest mass and magnetic fields in the Galaxy

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MS received 1 August 1972

Abstract. The effect of a photon rest mass on the dissipation of magnetic fields in the Galaxy is discussed and an upper limit on the rest mass is obtained: an earlier treatment is corrected and refined.

In the last few years considerable attention has been given to the question of the rest mass of the photon. In particular, effects on a galactic scale have been considered by Lee (1971) and Cole (1972) who discussed electromagnetic dispersion, by Gertsenshtein (1971) who suggested that the events detected by Weber might be caused by longitudinal electric waves, by Burman (1972a, b) who discussed the propagation of such waves, and by Williams and Park (1971) who discussed the dissipation of the galactic magnetic field. Dissipation of large-scale magnetic fields in the Galaxy will be re-examined here; in particular, it is pointed out that Williams and Park used a common mis-interpretation of the tensor conductivity.

Consider three-fluid plasmas, with the fluids consisting of electrons, protons and identical neutral particles; subscripts e, i and n will denote quantities pertaining to the electron, proton and neutral fluids, respectively; inertial effects and pressure gradients will be neglected. Collisions of particles of component fluid a with particles of component fluid b will be represented by a momentum relaxation frequency ν_{ab}. Then

$$-(e/m_{\mathrm{e}})(\boldsymbol{E}+c^{-1}\boldsymbol{u}_{\mathrm{e}}\times\boldsymbol{H})+\nu_{\mathrm{ei}}(\boldsymbol{u}_{\mathrm{i}}-\boldsymbol{u}_{\mathrm{e}})+\nu_{\mathrm{en}}(\boldsymbol{u}_{\mathrm{n}}-\boldsymbol{u}_{\mathrm{e}})+\boldsymbol{g}=0 \tag{1}$$

and

$$(e/m_{\mathrm{i}})(\boldsymbol{E}+c^{-1}\boldsymbol{u}_{\mathrm{i}}\times\boldsymbol{H})+\nu_{\mathrm{ie}}(\boldsymbol{u}_{\mathrm{e}}-\boldsymbol{u}_{\mathrm{i}})+\nu_{\mathrm{in}}(\boldsymbol{u}_{\mathrm{n}}-\boldsymbol{u}_{\mathrm{i}})+\boldsymbol{g}=0 \tag{2}$$

where e is the charge on a proton, c is the maxwellian speed of light, $\boldsymbol{E}$ and $\boldsymbol{H}$ are the electric and magnetic fields, $\boldsymbol{g}$ is the gravitational acceleration and m and $\boldsymbol{u}$ denote particle masses and fluid velocities. For a quasi-neutral plasma, the current density $\boldsymbol{j}$ and the bulk velocity $\boldsymbol{u}_{\mathrm{c}}$ of the combined electron–proton fluid are given by $\boldsymbol{j}=ne(\boldsymbol{u}_{\mathrm{i}}-\boldsymbol{u}_{\mathrm{e}})$, where n is the electron or proton number density, and $(m_{\mathrm{e}}+m_{\mathrm{i}})\boldsymbol{u}_{\mathrm{c}}=m_{\mathrm{e}}\boldsymbol{u}_{\mathrm{e}}+m_{\mathrm{i}}\boldsymbol{u}_{\mathrm{i}}$. Subtracting (1) from (2) leads to the generalized Ohm's law (Lehnert 1959, Alfvén and Fälthammar 1963)

$$\boldsymbol{E}+\frac{1}{c}\boldsymbol{u}_{\mathrm{c}}\times\boldsymbol{H}-\frac{m_{\mathrm{i}}-m_{\mathrm{e}}}{m_{\mathrm{i}}+m_{\mathrm{e}}}\frac{\boldsymbol{j}}{nec}\times\boldsymbol{H}=\sigma^{-1}\boldsymbol{j}+\frac{m_{\mathrm{i}}m_{\mathrm{e}}}{e(m_{\mathrm{i}}+m_{\mathrm{e}})}(\nu_{\mathrm{in}}-\nu_{\mathrm{en}})(\boldsymbol{u}_{\mathrm{c}}-\boldsymbol{u}_{\mathrm{n}}) \tag{3}$$

where the conductivity σ is given by

$$\sigma^{-1}=\frac{m_{\mathrm{e}}}{ne^{2}}\left\{\nu_{\mathrm{ei}}+\left(\frac{m_{\mathrm{i}}}{m_{\mathrm{i}}+m_{\mathrm{e}}}\right)^{2}\nu_{\mathrm{en}}+\frac{m_{\mathrm{i}}m_{\mathrm{e}}}{(m_{\mathrm{i}}+m_{\mathrm{e}})^{2}}\nu_{\mathrm{in}}\right\}; \tag{4}$$

the relation $m_i\nu_{ie} = m_e\nu_{ei}$, which follows from conservation of momentum, has been used.

The last term in (3) represents friction between the combined electron–proton fluid and the neutral fluid, and can be neglected because, in interstellar space, the electron–proton collision frequency is much larger than the electron–neutral and proton–neutral collision frequencies.

The resulting equation is often interpreted in terms of a conductivity for $\boldsymbol{j}\|\boldsymbol{H}$ and another conductivity for $\boldsymbol{j}\perp\boldsymbol{H}$; the former is σ while the latter depends on the magnetic field and is smaller than σ. Cowling (1962, see §3.1) has pointed out that this interpretation is unhelpful: a conductivity is normally related to either Joule dissipation or the associated diffusion of lines of $\boldsymbol{H}$, and for neither of these effects is the conductivity altered by the magnetic field. Equation (3), with the last term neglected, can be written

$$\boldsymbol{E}+c^{-1}\boldsymbol{u}_{\mathrm{H}}\times\boldsymbol{H} = \sigma^{-1}\boldsymbol{j} \tag{5}$$

where $\boldsymbol{u}_{\mathrm{H}} = \boldsymbol{u}_e+\{m_e/(m_i+m_e)\}(\boldsymbol{u}_i-\boldsymbol{u}_e)$. Equation (5) indicates that when σ is effectively infinite the magnetic flux is 'frozen-in' to closed contours moving with the velocity $\boldsymbol{u}_{\mathrm{H}}$; this velocity, which could be referred to as the velocity of the magnetic field, is closer to $\boldsymbol{u}_e$ than to $\boldsymbol{u}_c$. The conductivity relevant to both Joule heating and the rate of diffusion of lines of $\boldsymbol{H}$ is σ, defined by (4).

Taking the curl of (5), using Faraday's law and the Proca equation

$$\nabla\times\boldsymbol{H} = \frac{4\pi}{c}\boldsymbol{j}+\frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t}-\mu^2\boldsymbol{A} \tag{6}$$

in which $\boldsymbol{A}$ is the vector potential and μ^{-1} is the reduced Compton wavelength of the photon, results in

$$\frac{\partial\boldsymbol{H}}{\partial t} = \nabla\times(\boldsymbol{u}_{\mathrm{H}}\times\boldsymbol{H})+\frac{c^2}{4\pi\sigma}(\nabla^2\boldsymbol{H}-\mu^2\boldsymbol{H}) \tag{7}$$

when the displacement current and gradients of σ are neglected. If L denotes a distance over which $\boldsymbol{H}$ varies significantly, then the dissipative term in (7) implies that $\boldsymbol{H}$ decays as $\exp(-t/\tau)$ where $\tau \simeq (4\pi\sigma/c^2)/(\mu^2+L^{-2})$.

In interstellar space, $\sigma \simeq ne^2/m_e\nu_{ei}$; hence (Ginzburg 1970)

$$\sigma \simeq \frac{e^2}{m_e}\frac{T^{3/2}/5{\cdot}5}{\ln(220T/n^{1/3})}. \tag{8}$$

Thus, σ depends only slightly on n but depends strongly on T. For $L^2 \gg \mu^{-2}$, $\mu \simeq (4\pi\sigma/c^2\tau)^{1/2}$: the best upper limit for μ to be obtained from considering the dissipation of large-scale magnetic fields will result from investigating cool regions with long-lived fields; the variation of μ with T is more important than its variation with τ. Hence magnetic fields in HI regions are particularly relevant.

For galactic HI regions, $T \lesssim 10^2$K and $n \sim 10^{-3}$ to 10^{-2} cm^{-3} (Kerr 1968, see § 7.1, Rees and Sciama 1969) so that $\sigma \lesssim 5\times10^9$ s^{-1}; hence if the existence of large-scale magnetic fields with $\tau \gtrsim 10^6$ yr is established (Verschuur 1967), then $\mu \lesssim 10^{-12}$ cm^{-1}.

If these exists a general galactic magnetic field (Burbidge 1969, Parker 1969, Verschuur 1970, Cowling 1971), τ can be estimated to be at least equal to the rotation period of the Galaxy, namely 2×10^8 yr; also, T can be assumed to have been approximately the same for that time. Then, with $T \sim 10^2$K, $\mu \lesssim 10^{-13}$ cm^{-1}, which corresponds to $\mu^{-1} \gtrsim 1$ AU or a photon rest mass less than about 4×10^{-51} g. If there exists a medium with $T \sim 10^4$K, in which the cool HI regions are embedded (Clark 1965, Field 1969), then $\mu \lesssim 3 \times 10^{-12}$ cm^{-1}.

With present knowledge of the interstellar medium and field (Burbidge 1969, Weaver 1970), a plausible conservative upper limit for μ is obtained by considering magnetic fields with L a few hundred parsec, $T \lesssim 10^4$K and $\tau \gtrsim 10^6$ yr; this gives $\mu \lesssim 3 \times 10^{-11}$ cm^{-1}. The established upper limit on μ is 10^{-10} cm^{-1} (Goldhaber and Nieto 1971).

Williams and Park (1971) considered dissipation of a general galactic magnetic field and, having conservatively estimated τ to be at least 10^6 yr, gave an upper limit of 10^{-18} cm^{-1} on μ. But those authors used the 'transverse conductivity', which depends on the magnetic field and is many orders of magnitude less than the conductivity used here; as Cowling (1962, see §3.1) pointed out, it is the latter which relates to dissipation of energy; the direction of current flow relative to the magnetic field is irrelevant.

The above calculations suggest that there is little prospect of obtaining an upper limit on μ of much better than about 10^{-13} cm^{-1} from consideration of the dissipation of magnetic fields in the Galaxy; this figure is increased to about 3×10^{-12} cm^{-1} if there is a hot intercloud medium. The most that can be said at present appears to be that $\mu \lesssim 3 \times 10^{-11}$ cm^{-1}.

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