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LETTER TO THE EDITOR

A photon rest mass and the absorption of longitudinal electric waves in interstellar space

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Abstract. This letter treats the absorption of longitudinal electric waves in a cold plasma; upper limits for absorption in propagation from the galactic centre to the Earth are estimated.

In a recent letter (Burman 1972), the author used the Proca equations to discuss the dispersion of longitudinal electric waves in cold plasmas. The purpose of the present letter is to include the absorption arising through electron–heavy particle collisions, and to calculate upper limits for absorption in propagation from the centre of the Galaxy to the Earth. Gertsenshtein (1971) has suggested that the events detected by Weber might be caused by longitudinal electric waves.

The calculation of the refractive index formula proceeds as in the earlier letter (Burman 1972), except that the linearized equation of motion is now $(\mathrm{i}\omega+\nu)\boldsymbol{v} = e\boldsymbol{E}/m_{\mathrm{e}}$, where ν is the effective electron–heavy particle collision frequency and the notation is otherwise the same as before. It follows that, for longitudinal waves

$$n^2 = 1-\frac{\omega_{\mathrm{c}}^2/\omega^2}{1-(\omega_{\mathrm{p}}^2/\omega^2)(1-\mathrm{i}\nu/\omega)^{-1}}. \qquad (1)$$

Suppose that $\omega_{\mathrm{c}}^2/\omega^2$ and ν/ω are small and that ω is not close to ω_{p}. Then, if $-k$ denotes the imaginary part of n, equation (1) gives

$$k \simeq \frac{\nu}{2\omega}\frac{\omega_{\mathrm{c}}^2\omega_{\mathrm{p}}^2}{(\omega^2-\omega_{\mathrm{p}}^2)^2}. \qquad (2)$$

If $\omega^2 \ll \omega_{\mathrm{p}}^2$, then

$$\frac{\omega k}{c} \simeq \frac{\nu}{2c}\frac{\omega_{\mathrm{c}}^2}{\omega_{\mathrm{p}}^2} \qquad (3)$$

which quantity is independent of frequency. If $\omega^2 \gg \omega_{\mathrm{p}}^2$, then

$$\frac{\omega k}{c} \simeq \frac{\nu}{2c}\frac{\omega_{\mathrm{c}}^2\omega_{\mathrm{p}}^2}{\omega^4} \qquad (4)$$

which is strongly dependent on frequency. When ω is near ω_{p}, thermal effects on absorption and dispersion are important.

In interstellar space, the electron–neutral particle collision frequency can be neglected in comparison with the electron–proton collision frequency. In a plasma consisting of electrons and protons of equal number densities N, and with equal electron and ion temperatures T, if $T \ll 3\times10^5$ K, then the effective electron–proton collision frequency is given by (Ginzburg 1964)

$$\nu = 5{\cdot}5\frac{N}{T^{3/2}}\ln\left(220\frac{T}{N^{1/3}}\right) \tag{5}$$

where N is in particles per cubic centimetre (so that $\omega_p/2\pi \simeq 9\times10^3N^{1/2}$).

The electron temperature T_e and average electron number density N_e in HI regions of the Galaxy have been discussed by Rees and Sciama (1969). Prior to the discovery of pulsars, N_e was thought to be about 0·1 or 0·2 cm^{-3}, corresponding to $\omega_p/2\pi \sim 3\times10^3\ \text{s}^{-1}$; observations of the dispersion of radiation from pulsars have suggested that the value is lower. The number density N_H of hydrogen atoms in HI regions varies from about $10^3\ \text{cm}^{-3}$ to about $0{\cdot}3\ \text{cm}^{-3}$ or perhaps less (Rees and Sciama 1969).

There are two main processes which contribute to the ionization in HI regions (Rees and Sciama 1969): one is the ionization of some heavy elements by stellar ultraviolet radiation; the other is the ionization of hydrogen and helium by low-energy cosmic rays. The former process could give $N_i/N_H \simeq (2\text{–}4)\times10^{-4}$, where N_i denotes the number density of heavy ions; for $N_H \sim 10^{-1}$ to $10\ \text{cm}^{-3}$, the latter process has been calculated to give a value for N_e/N_H of at least $(0{\cdot}5\text{–}2)\times10^{-3}$ with $T_e \sim$ 10–30 K, and could give $(3\text{–}30)\times10^{-3}$ with $T_e \sim 100$ K (Rees and Sciama 1969). Observations of absorption at low frequencies and of Faraday rotation suggest that $N_e/N_H \sim 10^{-2}$ in HI regions.

A typical electron concentration in interstellar space could be about $10^{-3}\ \text{cm}^{-3}$ or about $10^{-2}\ \text{cm}^{-3}$. If $N_e \sim 10^{-3}$, corresponding to $\omega_p/2\pi \sim 300\ \text{s}^{-1}$, and $T_e \sim 10$ K, then (5) gives $\nu \sim 2\times10^{-3}\ \text{s}^{-1}$; if $N_e \sim 10^{-2}$, corresponding to $\omega_p/2\pi \sim 10^3\ \text{s}^{-1}$, and $T_e \sim 100$ K, then (5) gives $\nu \sim 5\times10^{-4}\ \text{s}^{-1}$.

In these two cases, since $\omega_c/2\pi < \frac{1}{2}\ \text{s}^{-1}$ (Goldhaber and Nieto 1971), the right side of (3) is $\lesssim 10^{-19}\ \text{cm}^{-1}$ and $\lesssim 3\times10^{-21}\ \text{cm}^{-1}$, respectively. Since the distance R from the centre of the Galaxy to the Earth is of the order of 10 kpc which is about 3×10^{22} cm, these two figures correspond to $\omega kR/c \lesssim 3\times10^3$ and $\lesssim 10^2$ respectively. Thus, for frequencies significantly below the interstellar plasma frequency, absorption could be important in propagation over R if the photon rest mass m (which is proportional to ω_c) is within one or two powers of ten of its established upper limit (Goldhaber and Nieto 1971).

For the above two models of the interstellar plasma, (4) gives $\omega kR/c \lesssim 3\times10^{13}/f^4$ and $\lesssim 10^{14}/f^4$, respectively, where $f \equiv \omega/2\pi$. In Weber's experiments, $f = 1{\cdot}65\times10^3\ \text{s}^{-1}$ which, for the lower-density model, seems significantly above the plasma frequency and corresponds to $\omega kR/c \lesssim 3$: absorption could be heavy if m is more than about one third of its established upper limit. For the higher-density model, the frequency in Weber's experiments is close to the plasma frequency: the cold plasma model is inadequate to treat either absorption or dispersion. Also, for the lower-density model of the interstellar plasma, because of variations of the electron density, a wave with $f \sim 10^3\ \text{s}^{-1}$ will cross regions in which the cold plasma model is inadequate.

In HII regions, taking $N_e \sim 10\ \text{cm}^{-3}$, corresponding to $\omega_p/2\pi \sim 3\times10^4\ \text{s}^{-1}$, and $T_e \sim 10^4$ K, equation (5) shows that $\nu \sim 10^{-3}\ \text{s}^{-1}$. For the frequency in Weber's experiments, (3) is applicable and becomes $\omega k/c \lesssim 3\times10^{-24}\,\text{cm}^{-1}$: HII regions make a negligible contribution to the absorption.

Further investigations of longitudinal electric waves when $m \neq 0$, in intergalactic as well as interstellar space, are in progress. In particular, propagation in warm plasmas is being studied.

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