1974SoPh...34..421M

COMMENTS ON 'NEUTRALIZATION AND STABILIZATION OF PARTICLE STREAMS IN THE CORONA AND TYPE III RADIO BURSTS' BY DEAN F. SMITH

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(Received 20 October, 1973)

Abstract. Electron streams which excite type III bursts experience a negligible energy loss in accelerating a return current. Furthermore the plasma oscillations generated as the return current turns on and off are too weak to be of significance as a source of the observed radiation.

1. Introduction

Smith (1972), hereinafter referred to as Paper S, appealed to models for current-neutralized electron beams in the laboratory in discussing current-neutralization of streams of charged particles in the solar corona. One particular feature of the models used is the generation of a large amplitude plasma oscillation (LAPO) at the front of the stream. In Paper S the following implications of the LAPO were suggested:

(i) A precursor phenomenon (whose observation was attributed to Boischot) in type III bursts may be due to plasma radiation from the LAPO,

(ii) The number density n_s in any stream of electrons cannot exceed $10^{-5}\, n_e$, where n_e is the number density of the ambient electrons, and

(iii) The number density of relativistic electrons 'stored' in the corona cannot exceed 10^2 cm^{-3}.

The inequalities in (ii) and (iii) were deduced from the estimated energy loss in generating the LAPO.

The "energy lost W_r in travelling a distance d cm^{-2} of cross-section area due to the acceleration of the reverse current" was estimated in Equation (S12) as

$$W_r = 2\beta n_e m_{e,i} v_r^2 d. \tag{1}$$

(W_r is the energy lost per unit cross-sectional area of the stream after it has travelled a distance d.) Here, as in Paper S, $m_e(m_i)$ denotes the mass of the electron (ion, if the stream is composed of ions), v_r is the reverse drift velocity of the ambient electrons (see Section 2 below) while "β is some fraction of α depending on the abruptness of the stream" where $\alpha = \omega_p \tau$ is the ratio of the (angular) plasma frequency ω_p to the collision frequency τ^{-1}. A value $\beta = 2 \times 10^2 = 2 \times 10^{-5}\, \alpha$ was chosen "to explain Boischot's observations".

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Solar Physics **34** (1974) 421–425. *All Rights Reserved*

My comments on the above are twofold. Firstly, Equation (1) gives an incorrect estimate of the rate of energy loss; it should be replaced by

$$W_r = (\beta/\alpha) n_e m_{e,i} v_r^2 d, \tag{2}$$

which is smaller than (1) by a factor $(2\alpha)^{-1}$ ($\approx (2 \times 10^7)^{-1}$ in the corona). Secondly, the estimate $\beta/\alpha \approx 2 \times 10^{-5}$ is unrealistically high for streams in the corona as it assumes the stream has a 'front' only 50 m thick. A value at least ten orders of magnitude smaller would be more plausible.

These points are amplified in Section 3, after the properties of the models used are summarized in Section 2.

2. Acceleration of the Reverse Current

The development of models for electron beams carrying large currents has been motivated by laboratory experiments (see e.g. the review by Benford and Book, 1971). The models of Cox and Bennett (1970), Hammer and Rostoker (1970) and Lee and Sudan (1971) are of particular relevance in the following discussion. In these models the following general assumptions are made:

(a) The stream of electrons is of low density ($n_s \ll n_e$), is mono-energetic (velocity v_s) and is cylindrically symmetric with n_s independent of radial distance r for $r < R$, and zero for $r > R$.

(b) The background plasma consists of cold electrons (number density n_e) and immobile ions. A collisional relaxation term is included in the equations; in the present case the important consequence of this is that the LAPO damps out due to collisions with an e-folding time τ.

Relevant conclusions, which either were stated explicitly or can be deduced readily from the three papers cited, are as follows:

(i) Cox and Bennett showed that if the direct current I (with $I = -\pi R^2 n_s e v_s = -eN_s/t_s$, where N_s is the number of electrons in the stream, t_s is the time taken for the stream to pass a fixed point, and where $-e$ is the electronic charge) is much less then the Alfvén-Lawson current I_A (Alfvén, 1939; Lawson, 1957), which is given by

$$I_A = 5.1 \times 10^{13} \beta\gamma \text{ esu} \quad (= 1.7 \times 10^4 \beta\gamma \text{ A}), \tag{3}$$

with $\beta = v_s/c$ and $\gamma = (1-\beta^2)^{-1/2}$, then the induced return current flows primarily outside the cylinder (i.e. at $r > R$), while for $I \gg I_A$ the return current is confined to $r \lesssim R$ and the current neutralization is local in the sense that the ambient electrons flow with velocity

$$v_r = -\frac{n_s}{n_e} v_s. \tag{4}$$

For type III bursts $\sim 10^{33}$ electrons per flare with $\beta \approx 0.3$ (Lin and Hudson, 1971) divided by ~ 10 to ~ 100 detectable bursts per flare each with a duration of ~ 1 s at

80 MHz (Wild, 1969) implies

$$\frac{I}{I_A} = 10^{8.5 \pm 1.5},$$

where a rough estimate of the uncertainty is indicated. Hence in this case the neutralizing current flows inside the stream.

(ii) If the front of the stream is 'sharp' (e.g. n_s is a step function of z), then the return current at a fixed point turns on during a time ω_p^{-1} after the arrival of the front of the stream. However, as stated in Paper S, the ambient electrons do not acquire the velocity (4) smoothly, but their velocity oscillates (at the plasma frequency) between 0 and $2v_r$. There is an associated electric field (along the z-axis) which also oscillates at the plasma frequency. This oscillatory motion corresponds to a large amplitude longitudinal electron plasma oscillation. The energy density W_{PO} in the LAPO is equal to that in the return current W_{RC}:

$$W_{\mathrm{RC}} = \tfrac{1}{2} n_e m_e v_r^2 . \tag{5}$$

(iii) Collisions cause the LAPO to damp out over a distance $v_s\tau$ (no other damping mechanism is included in the models). The reverse-drift motion of the ambient electrons is randomized by collisions over the much greater distance $v_s\tau(R\omega_p/c)^2$ (Lee and Sudan, 1971). Thus if the stream is of length $l_s \ll v_s\tau(R\omega_p/c)^2$ only collisions are of relevance in the damping of the LAPO. [In type III bursts l_s is probably of order $v_s\tau$ and is certainly much less then $v_s\tau(R\omega_p/c)^2$.]

(iv) For a stream with a sharp rear and with $l_s \ll v_s\tau(\omega_p R/c)^2$, the return current turns off and another LAPO is set up as the back edge of the stream passes. The amplitude of this LAPO is equal to that of the first. Thus, if interference between the two were ignored, the total energy density deposited in LAPO's would be $2W_{\mathrm{RC}}$.

Although a background magnetic field was included in the models (e.g. by Lee and Sudan, 1971) the results are not necessarily relevant here because the gyroradius of the (stream) electrons was assumed to be much greater than R. For electrons in type III streams the gyroradius is much less than the radius of the stream (e.g. ~1 km compared with $\sim 10^5$ km). In any event inclusion of a background magnetic field weaker than the self-field which would exist if there were no neutralization, i.e.

$$B = \frac{2I}{Rc}, \tag{6}$$

would not alter the above results. [For type III bursts the above estimate of I together with $2R \sim 3 \times 10^5$ km at 80 MHz (Wild, 1969) gives

$$\frac{2I}{Rc} = 10^{1.5 \pm 1.5}\ \mathrm{G},$$

whereas Kai (1970) estimated the actual field as $B < 0.14$ G and Melrose and Sy (1972) estimated $B < 0.04$ G.]

A 'sharp' front may be defined as one which gives an LAPO whose amplitude is roughly the same as for a step-function in n_s. [It might be commented that in many laboratory experiments the stream propagates into an un-ionized gas and causes the ionization itself. The assumption of a 'sharp' front to describe this very complicated situation is merely one of convenience.] Cox and Bennett (1970) considered various profiles for the stream; their analysis can be extended to define a 'sharp' profile. Let the component E_z of the electric field along the z-axis be identified as the amplitude of the LAPO. Neglecting collisions it can be shown (e.g. by retaining $n_s(z_0)$ inside the z_0-integral in Equation (A12e) of Hammer and Rostoker) that E_z has the following z-dependence:

$$E_z(z) \sim \int_{-\infty}^{\infty} \mathrm{d}z_0 n_s(z_0) \cos \frac{\omega_p}{v_s}(z_0 - z). \tag{7}$$

Let the 'abruptness' of the stream be characterized by the distance

$$L_c = n_s \left| \frac{\mathrm{d}n_s}{\mathrm{d}z} \right|^{-1}. \tag{8}$$

A step-function corresponds to $L_c = 0$. It follows from (7) that for $L_c \ll v_s/\omega_p$ the amplitude differs little from the case $L_c = 0$. Thus, a 'sharp' change may be defined as one which occurs over a distance less than v_s/ω_p. [One has $v_s/\omega_p \sim 10$ cm for type III bursts at 80 MHz.]

For a smoothly rising and falling stream, by which is meant the case $L_c \gg v_s/\omega_p$, the amplitude (7) is smaller than for a 'sharp' stream, e.g. by a factor of order $v_s/\omega_p L_c$ for a stream with a triangular profile with $L_c = l_s/2$ and by an even smaller factor for a smoother profile. Consequently the energy density generated in the LAPO'S for a smoothly varying stream is less than or of the order of

$$W_{\mathrm{PO}} \approx 2\left(\frac{v_s}{L_c \omega_p}\right)^2 W_{\mathrm{RC}}. \tag{9}$$

3. Energy Losses

In the models discussed above the front of the stream loses energy both to an LAPO and in accelerating the return current, while the rear of the stream also loses energy to an LAPO but gains energy as the return current turns off. Thus the net energy loss is only that to the LAPO'S. Following Paper S let the actual energy density generated in LAPO'S be a fraction β/α of the energy density for a sharp stream, i.e.

$$W_{\mathrm{PO}} = 2(\beta/\alpha) W_{\mathrm{RC}}. \tag{10}$$

In travelling a distance d the energy lost per unit cross-sectional area is $W_{\mathrm{PO}} d$, which with (5) and (10) reduces to the expression (2).

The use in Paper S of Equation (1) rather than Equation (2) to estimate this energy (with the resulting overestimate of the loss) is evidently due to an implicit assumption that the energy needs to be resupplied to the LAPO once every plasma period for $\alpha = \omega_p \tau$ periods, i.e. until the LAPO is damped. However, the energy needs to be supplied by the stream only once. (The time taken to set up the LAPO is $\sim L_c/v_s$, and the fractional loss due to collisions in this time is $\sim L_c/v_s \tau$. For $L_c \sim l_s \gtrsim v_s \tau$ collisions impede even the setting up of the LAPO.)

The assumption $\beta = 2 \times 10^2 = 2 \times 10^{-5}\ \alpha$ in Paper S corresponds to a characteristic length $L_c \sim 250 v_s/\omega_p \sim 50$ m (this follows from Equations (9) and (10) for $\beta/\alpha = 2 \times 10^{-5}$ for a plasma frequency of 80 MHz). One has no reason to believe that the front (or rear) of a type III stream is so sharp. Even if it were initially this sharp, the velocity dispersion Δv_s (which has been measured near the orbit of Earth by Lin *et al.* (1973)) would tend to smooth it out in a time $\sim L_c/\Delta v_s$ which is less than a microsecond. Indeed 'sharp' fronts are not observed in the laboratory experiments, see, e.g., Cox and Bennett (1970). In type III bursts L_c should be comparable with the length of the stream. Thus a resaonable estimate might be $L_c \sim 10^9$ cm. This would give $\beta/\alpha \sim 10^{-16}$ which is eleven orders of magnitude less than the value chosen in Paper S.

With the above correction (i.e. the replacement of Equation (1) by Equation (2)) and with a more plausible estimate of β/α for type III bursts, the energy loss by the stream in accelerating the return current is entirely negligible and the energy deposited in the large amplitude plasma oscillation could lead to no detectable plasma radiation.

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