Influence of "short-circuiting" effect on the dynamics of an artificial comet (the AMRTE experiment)

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A model of a short-circuiting of the currents and of the electric-field distribution is proposed. This model explains the basic features of the dynamics of an artificial comet in the AMRTE experiment.

1. Research on Halley's comet has recently attracted increased interest to a question of importance to geophysics and astrophysics: that of the acceleration of an immobile plasma cloud by a plasma stream directed across a magnetic field $\mathbf{B}_0$. The ARMTE experiment,[1] involving the injection of barium clouds into the solar wind, was carried out in 1984–1985 in an effort to simulate this phenomenon.

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A cloud of low density ($A = n_I/n_0 \ll 1$; the indices 0 and i refer to the solar wind, while I refers to the cloud) is known to acquire a flow velocity $\mathbf{v}_0$ as a result of drift in the electric field $\mathbf{E}_0 = -(1/c)\mathbf{v}_0 \times \mathbf{B}_0$. In the opposite limit ($A \gg 1$), the field $\mathbf{E}_0$ is canceled by the polarization field $\mathbf{E}'$ in the cloud, and the acceleration is linked[1] with a momentum transfer by Alfvén waves. The AMRTE experiment revealed that (1) the duration of the acceleration of the cloud (along $\mathbf{v}_0$) is much longer than the Alfvén time[1)] (Ref. 1) and (2) the cloud moves in the direction opposite $\mathbf{E}_0$, at a typical velocity of 2–3 km/s$\approx 10^{-2} v_0$.

In this letter we wish to propose a model to explain these results. This model can be outlined as follows: The drift of the cloud occurs in a perturbed electric field $\mathbf{E} = \mathbf{E}_0 + \mathbf{E}'$. The field $\mathbf{E}' - \nabla\Psi$ is determined by a "short-circuiting" effect[2] involving a short-circuiting of the currents through the plasma of the solar wind. An instability of the longitudinal currents in the solar wind (the anomalous resistance[3]) results in a lengthening of the acceleration time.

2. We consider a dense ($A \gg 1$) plasma cloud with length scales $a_\parallel$ and $a_\perp \sim a_\parallel$ with respect to the perturbed magnetic field $\mathbf{B}$ ($B/B_0 \gg 1$). The fields $\mathbf{B}$ and $\mathbf{E}$ "decay" to the background level over length scales $l_\parallel$ and $a_\perp$ (Fig. 1). In accordance with the experimental conditions of Ref. 1, we assume that the ion gyroradii satisfy $\rho_{I,i} = (v/\omega_c)_{I,i} \lesssim a_\perp$ and $\rho_i^{(0)} = v_0/\omega_{ci}^{(0)} \gg a_\perp$ in the strong-B region (the "head" of the comet), where ω_{cj} is the gyrofrequency of ion j.

From the condition for the closure of the current system in Fig. 1b we find

$$\nabla_\parallel \Gamma_\parallel^{(e)} \doteq \nabla_\perp (\Gamma_\perp^{(i)} + \Gamma_\perp^{(I)}). \tag{1}$$

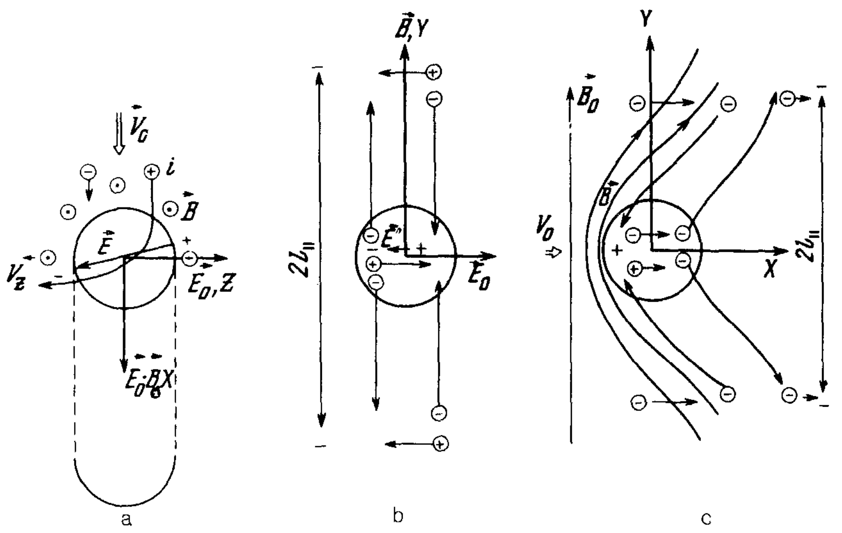

FIG. 1. a—Experimental geometry (the dashed line is the tail of the comet); b—current system in the z, y plane; c—magnetic field lines and current system in the x, y plane.

Here $\Gamma_{\parallel}^{(e)} = n_e e E'_{\parallel}/m\nu_e$, ν_e is the effective electron collision rate,

$$\Gamma_{\perp}^{(j)} = \left[\frac{n_j}{\omega_{cj}} \left\{ \frac{\partial \mathbf{v}_{\perp}}{\partial t} + (\mathbf{v}_{\perp}\nabla)\, \mathbf{v}_{\perp} \right\} \times \frac{\mathbf{B}}{B} \right]$$

is the inertial current of the ions of species j, and $\mathbf{v}_{\perp} = c\mathbf{E}\times\mathbf{B}/B^2$.

In the plasma of the solar wind we can use the estimates $\nabla_{\parallel} \sim 1/l_{\parallel}$ and $\nabla_{\perp}\Gamma_{\perp}^{(i)} \sim n_0 v_0/a_{\perp}$, while in the cloud we can use $\nabla_{\parallel} \sim 1/a_{\parallel}$ and $\nabla_{\perp}\Gamma_{\perp}^{(I)} \approx \partial/\partial z \Gamma_z^{(I)}$. As a result, we find from (1)

$$\begin{aligned} l_{\parallel} &\approx a_{\perp} (\omega_{ce}^{(0)}/\nu_e)^{1/2} \\ \partial v_x/\partial t &\lesssim \omega_{cI} v_0 (l_{\parallel}/a_{\parallel} A) \end{aligned} \tag{2}$$

(here we are using $\mathbf{E}'_z \approx -\mathbf{E}_0$ and, by virtue of the electrostatic nature of the problem, $E'_{\parallel} = E'_z a_{\parallel}/l_{\parallel}$). The acceleration of a dense cloud is thus weaker by a factor of $\sim A(\nu_e/\omega_{ce}^{(0)})^{1/2}$ than that of a low-density cloud. The velocity at which the cloud is "carried off" by the solar wind, which is established over a time $\sim a_{\perp}/v_{\perp}$, is found from (1) to be, under the condition $v_x \gg v_z$,

$$v_x \sim v_* = v_0 \left(\frac{l_{\parallel} a_{\perp}}{A a_{\parallel} \rho_i^{(0)}} \frac{M_i}{M_I} \right)^{1/2}. \tag{3}$$

The velocity of the transverse displacement, v_z, is determined by the component E_x, whose magnitude can be found by analyzing the current system in Fig. 1c. The latter results from the stopping of the electrons of the solar wind in the strong-B region; in the absence of a longitudinal component ($\parallel\mathbf{B}$) of the flow, the latter causes an adiabatic increase in the density ($n_e \sim B$). However, since the ion density of the solar wind remains on the order of n_0 ($\rho_i \sim a_{\perp}$), the electrons spread out along B, and we have $\Gamma_{\parallel}^{(e)} \sim n_0 e E'_x a_{\perp}/m\nu_e l_{\parallel}$. From the condition for the closure of the current of solar-wind electrons,

$$-\nabla_{\parallel}\Gamma_{\parallel}^{(e)} = \nabla_{\perp}\Gamma_{\perp}^{(e)} \sim \frac{\partial \Gamma_x^{(e)}}{\partial x} \sim n_0 v_x^{(e)}\, \partial/\partial x \ln B \sim n_0 \frac{cE_0}{a_{\perp} B},$$

and (2) we find $E'_x \sim E_0 B_0/B$. The drift velocity

$$\mathbf{v}_z = \frac{c\,[\mathbf{E}_x \times \mathbf{B}]}{B^2} \simeq -v_0 \left(\frac{B_0}{B}\right)^2 \frac{\mathbf{E}_0}{E_0} \tag{4}$$

is thus independent of the density.[2)]

It follows from (3) and (4) that in a sufficiently dense cloud $A > (l_{\parallel} M_i/a_{\parallel} M_I)\cdot(B/B_0)^3$ the drift contribution, $v_z \partial/\partial z$, dominates the inertial current $\Gamma_z^{(I)}$, and we replace (3) by

$$v_x \sim \frac{v_*^2}{v_0}\left(\frac{B}{B_0}\right)^3 . \tag{5}$$

3. Let us compare the results with the results of the experiment of Ref. 1, for which the typical parameter values are ($t = 100$ s) $a_\perp \sim a_\parallel \sim 100$ km, $B \approx 10B_0 \approx 100$ nT, $A \approx 2\times 10^3$, $n_0 \approx 5$ cm^{-3}, and $v_0 \approx 300$ km/s. The effective collision rate of the solar-wind electrons can be estimated from[3] $\nu_e = \alpha\omega_{p0}$, where ω_{p0} is the plasma frequency in the solar wind, and $\alpha \sim 10^{-3}$. From (2), (4), and (5) we find $v_z \approx 10^{-2}\cdot v_0 \approx 3$ km/s and $v_x \sim 1$ km/s, in agreement with experiment. As time elapses, the density of the cloud decreases because the particles flow off into the tail, and the velocity at which the cloud is "carried off" increases, again in agreement with (5) ($v_x \sim 1/A$).

The skin time $\tau_s \sim (\omega_{p0}^2 a_\perp^2/\nu_e c^2) \sim 10$ s is shorter than $a_\perp/v_z \sim 40$. This circumstance justifies our use of the electrostatic approximation.

We conclude with a discussion of ν_e. It follows from (1) and (2) that the current velocity of the solar-wind electrons,

$$v_\parallel^{(e)} = \frac{eE'_\parallel}{m\nu_e} \sim v_0\left(\frac{\omega_{ce}^{(0)}}{\nu_e}\right)^{1/2},$$

is a significant fraction of the thermal velocity of these particles ($v_{Te} \approx 10\ v_0$) and significantly above the threshold for the onset of current-driven (low-frequency) instabilities in the plasma of the solar wind and for the onset of an anomalous resistance.[3] The AMRTE experiment did in fact reveal[4] a low-frequency turbulence, at a level high enough to cause an effective scattering.

[1)]According to Ref. 1, the cloud should have moved several thousand kilometers over the observation time (5 min), but the actual displacement was less than 100 km.

[2)] This assumption is valid only under the condition $v^* \ll v_0$.

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