Theoretical Estimation of Passive HF signal from a Meteorite Plasma Trail

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***Abstract*— The plasma trails of bright meteorites are known to produce HF signals in the 3-300 MHz regime. We explore the possibility that these signals are coherent or partially-coherent Langmuir oscillations of an extended electron cloud along the plasma tail, driven by the differential motion of fast-moving charges through a uniform magnetic field.**

Keywords—meteorites; HF detection; VHF; plasma physics; RF electromagnetics;

I. INTRODUCTION

Remote signals have been observed from meteorite plasma wakes in the HF and VHF ranges [1-2]. This paper explores two new factors which may help to understand the source of the generation mechanism – wake coherence and the role of the Earth's magnetic field. We have calculated the magnitude of these oscillations for a spatially extended, constant-velocity, uniform-density plasma and find that it should be substantial. The results are generalized to estimate the remote signal associated with the CFD (computational fluid dynamic) predicted plasma distribution behind a meteorite traversing the upper atmosphere at high speeds. The proposed mechanism, the coherent or partially-coherent, plasma oscillation of a long, extended electron cloud, is a permitted mode of the system.

II. ANALYSIS

The Earth's magnetic field acts upon free electrons in a plasma wake which travels behind the meteorite, driving electron oscillations in the wake. We have calculated the magnitude of these oscillations for a spatially extended, constant-velocity, uniform-density plasma and find that it should be substantial. The proposed mechanism – the coherent or partially-coherent, plasma oscillation of a long, extended electron cloud – is a permitted mode of the system.

A. Low Temperature and Plasma Density Limit

We first consider the limit of low temperature and plasma density by solving the Lorentz equations:

$$r_x''(t) = -\nu r_x'(t) - \omega_c r_y'(t) - \omega_p^2 r_x(t) - \omega_c v_{y,wake} \tag{1a}$$

$$r_y''(t) = -\nu r_y'(t) + \omega_c r_x'(t) - \omega_p^2 r_y(t) + \omega_c v_{x,wake} \tag{1b}$$

for cyclotron frequency ω_c associated with the Earth's magnetic field perpendicular to the wake velocity $\vec{v}_{wake}$, electron position $r_j(t)$ relative to the wake, plasma frequency ω_p, and collision frequency ν .

Calculating the eigenvectors in the homogenous ($\vec{v}_{wake} = 0$) case, we obtain an exact solution for the inhomogeneous case. We numerically verify the solution. A simple analytical result emerges where the plasma frequency exceeds the cyclotron frequency and the electron-electron and electron-ion collision rates. In that scenario, the electron displacement component r_y is given by:

$$r_y(t) = \frac{\omega_c v_{x,wake}}{\omega_p^2}\left(1 - \cos\left(\omega_{p,y} t\right)\right) . \tag{2}$$

B. Moderate Temperature and Plasma Density

A thermalized, finite plasma with ion density $n_i(r,z) = n_0\big(\Theta(z) - \Theta(z-L)\big)$ has been considered in one dimension absent a magnetic field and shown to permit oscillations at the Langmuir frequency. Electron displacements in the plasma wake will be bound by the Debye length absent a source of quasi non-neutrality.

Based upon a perturbative solution of the fluid flow equations in three dimensions, one also may demonstrate that coherent Langmuir oscillations are a permitted and contributing mode of the system. For a cylindrical plasma in the low-temperature and low-magnetic-field limit, for example, one obtains collective oscillations like:

$$n_e(r,z,t) = n_0\big(\Theta(r) - \Theta(r-R)\big)\begin{pmatrix}\Theta(z + \Delta z\, sin(\omega t) - L) \\ -\,\Theta(z + \Delta z \sin(\omega t))\end{pmatrix} \tag{3a}$$

$$n_i(r,z,t) = n_e(r,z,0) , \tag{3b}$$

where $\Theta(z)$ is the Heaviside step function, as a test solution to the fluid flow equations below:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}_e) = 0, \tag{4a}$$

$$\vec{\nabla} \cdot \vec{E} = \frac{e}{\epsilon_0}(n_i - n_e) \tag{4b}$$

$$m n_e\left(\frac{\partial \vec{v}_e}{\partial t} + \left(\vec{v}_e \cdot \vec{\nabla}\right)\vec{v}_e\right) = -e n_e \vec{E} , \tag{4c}$$

where $\vec{v}_e$ is the electron fluid velocity.

The application of a magnetic field to the treatment will modify the shape and perturb the frequency of these existing modes.

C. Signal Estimation

The remote field is calculated for a realistic, non-uniform density plasma of arbitrary orientation. In the simple case of a wake of length L and radius R oriented along the $\hat{z}$ axis. with current density components $J_{0,j}\, e^{-i\omega_p t} = n_e\, r_j'(t)_{\max} e^{-i\omega_p t}$

and wavevector $k = \omega_p/c$, the vector potential from which we derive the fields is given by:

$$A_j(\vec{x},t) = \frac{\mu_0 J_{0,j}}{2\pi k cos\theta} e^{-i\omega_p t} \frac{e^{ikr}}{r} \pi R^2 \sin(kL \frac{\cos\theta}{2}). \quad (5)$$

The output power corresponds to the Larmor formula with electron velocity based upon Equations (1-2) bound by the Debye length, and is modified to account for spatial extent via the geometric dependence that results from taking the curl of the curl of Equation (5).

The $\sin^2\theta$ oscillatory antenna pattern narrows for $kL > 1$ due to interference, with maxima located perpendicular to the current and the wake direction. The total output radiated power P_{kL} at long distances scales as $g(kL) = P_{kL}/P_{dipole}$ for

$$\frac{P_{kL}}{P_{dip}} = g(2kL)\,,\; g(x) = \frac{3\left(x\cos(x) - \sin(x) + x^2 \int_0^x \frac{\sin(t)}{t} dt\right)}{2x^3}, \quad (6)$$

which reaches half-maximum at $kL \approx 2.5$ and falls off slowly thereafter.

Leveraging steady-state CFD simulation data of the electron density in a plasma wake due to a blunt object traveling through the atmosphere, a magnitude and effective length is assigned to each frequency band. Scaling the power output of each band according to its geometry yields results like that of Figure 1. The remote signal is found to be significant for coherent oscillations.

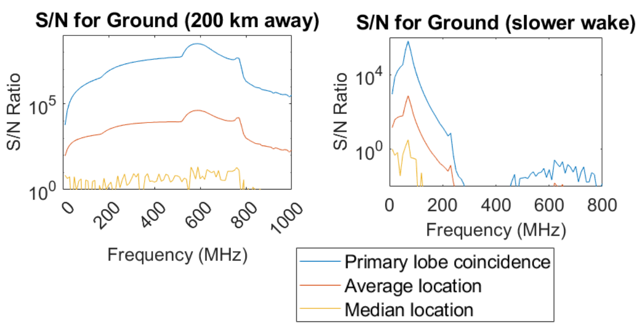

Figure 1. Example scenarios: Remote signal-to-thermal-noise associated with coherent plasma oscillations within a frequency bin or surface given a blunt, meter-scale front traveling through the atmosphere at kilometers per second. The receiver is 200 km away with 10 m^2 effective area.

The Mach number of the wake correlates with the peak frequency and signal-to-thermal-noise ratios.

Additional terms and contributions are found to be negligible, such as the remote field associated with a plasma tail traversing a magnetic anomaly map.

III. Discussion

Further study is needed to investigate surface currents, to incorporate the wake reflection of low frequency components, and to assess the coherence of oscillations in a given frequency bin. Possible coherence mechanisms are rapid ionization, or a plasma bunching mechanism [3] due to the combined magnetic and radiation field interaction. The effect of 'dusty plasma' has not been included in the plasma analysis. Ablated particulates and heavy neutrals in the plasma species typically increase plasma lifetime and likely will serve to enhance the signal [4].

The plasma frequencies predicted by the CFD model and predicted signals like that of Figure 1 correspond well to those measured in meteorites in the HF and VHF. Photoelectrons play a secondary role in the process [5]. One does not expect to see significant signal in the VLF from either mechanism, which is consistent with studies which show the previously observed VLF signals were due to lightning and not meteorites [6].

Recent experimental results suggest that the HF signal associated with meteorite wakes is in general isotropic [7]. This would either suggest an alternative HF generation mechanism, or may be consistent with the mechanism proposed here, dominated by dipole-like contributions (i.e., effective lengths below $2.5/k$), off-lobe emissions, and/or oscillations from a chemical product enhanced wake that are mostly incoherent.

IV. Conclusions

In this paper, we have suggested that meteorite HF emission is due to coherent or partially-coherent Langmuir oscillations of an extended electron cloud.

However, the coincidence of HF signal with persistent trains – long-lasting, visible and/or infrared signals – suggests that exothermic chemical reactions between atmospheric oxygen play an essential role in the HF generation [2].

We would suggest that supra-thermal electrons and/or other chemical byproducts associated with persistent train generation enhance and/or contribute to coherent electron Langmuir oscillations of the extended plasma tail, which are driven by the differential motion of charges through a magnetic field.

Acknowledgment

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