Magnetic Dipole Antennas in Moving Plasmas: a Laboratory Simulation

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The magnetic perturbation to a large laboratory plasma due to a pulsed $(1/\omega_i \gg \Delta t \gg 1/\omega_p)$ magnetic dipole is repeatedly superposed in space and time to simulate the motion of a dc-driven dipole. "Shock"/"wing" structures are formed when the dipole moves along/across the ambient magnetic field, $\mathbf{B}_0$.

INTRODUCTION

The effect created by a moving magnetic field in a plasma has long been an important topic of space physics research. The best known example is the study of the interaction of Earth’s dipolar magnetic field with the solar wind. Proposals to create artificial magnetospheres in space [Lane et al., 1987; Birykov et al., 1992] are made from time to time while laboratory works can be traced to Birkeland’s famous “terrella” experiments [Egelrud, 1984]. Similarly, modulation of magnetic sources (e.g., a dipole) is thought to produce VLF/ELF waves [Armand et al., 1989; Triska and Shevchenko, 1990], important for advanced communications. More recently, magnetic signatures observed during the flyby of 951 Gaspra by Galileo imply that asteroids may carry a magnetosphere [Kivelson et al., 1993]. Although these perturbation sources do not, in general, exhibit a variation in time, the plasma in which they are immersed sees them as time-dependent and, consequently, responds differently to each. Thus, a slow moving, large source induces waves at or below the Alfvén frequency while a fast, small one produces R, X, and/or O waves. The intermediate regime of whistler waves, believed to apply to objects such as 951 Gaspra [Kivelson et al., 1993], is the subject of our work. We approach the problem from a novel direction: instead of creating a moving plasma that buffers a stationary source and then mapping the perturbation, we create a wave packet by pulsing the source in a stationary plasma, measure it, and then digitally superpose the observations to study motion along and across the ambient magnetic field $\mathbf{B}_0$. In this way, a single, detailed data set allows us to study various ratios of source-to-plasma speed. The analysis reveals that structures that resemble the wake of boats in water (“wings” in three dimensions) are produced when the source moves across $\mathbf{B}_0$. Motion along $\mathbf{B}_0$ produces something reminiscent of a shock, albeit without the nonlinear features (e.g., particle reflections or plasma parameter modification).

EXPERIMENTAL ARRANGEMENT

The experiments are conducted in the afterglow ($t_{\text{decay}} \approx 2.5$ ms, $t_{\text{afterglow}} = 150$ μs) of a large, cylindrical (1 m diam., 2.25 m length), magnetized ($B = 20$ G), plasma column ($n_e = 6 \times 10^{11}$ cm$^{-3}$, $kT_e = 1.3$ eV) [Stenzel et al., 1993]. The magnetic perturbation is launched by applying a short current pulse ($I_{\text{max}} \approx 0.1$ A, $\Delta t = 0.1$ μs) to a two-turn, insulated magnetic dipole antenna (4.5 cm diam., $B_z \approx 50$ mG in vacuum at its center) located at the center of the plasma column. The perturbation is measured with a magnetic probe containing three orthogonal loops at many points ($\geq 15,000$) surrounding the source and averaged over ten highly repeatable discharges. The stored measurements of $\partial \mathbf{B}(r,t)/\partial t$ are then processed to yield $\mathbf{B}(r,t)$ over a regularly spaced grid. The current density, $\mathbf{J}(r,t)$, is then available from Ampere’s law, $\nabla \times \mathbf{B}(r,t) = \mu_0 \mathbf{J}(r,t)$.

EXPERIMENTAL RESULTS

Previous work has shown that, for our experimental parameters, magnetic perturbations are carried via whistler waves [Urrutia and Stenzel, 1989]. This conclusion was reached on the basis of interferometric studies of pulse trains that yielded the appropriate dispersion and polarization. Spectral analysis employing Fast Fourier Transformations in both $k$ and $\omega$ space (see Rousculp et al., in this volume) of a single wave packet has now confirmed this. In this paper, however, we restrict the discussion to the temporal and
spatial evolution of the single pulse wave packet and its superposition. Figure 1 displays records of $B_x(t)$ at various points along a line parallel to $B_0$ ($x \approx 0, y \approx -3, z$; antenna is at origin). The dashed lines tag similar points in the packet and make a $z - t$ graph of its motion along the chosen line in $z$. Since the lines have different slopes (equivalent to speeds), the packet disperses. Hence, it may be deduced that it consists of waves that propagate at different group velocities. The spatial evolution of $B_x$ is depicted in Figure 2a for a plane bisecting the dipole and containing the points displayed in Figure 1. Inspection of the propagating packet shows that it travels across and along $B_0$. Tracking the minimum and maximum of $B_x$, as described by Stenzel et al. [1993], reveals that the packet moves within a cone of angle $\theta < 19^\circ$ consistent with classical, oblique whistler propagation [Helliwell, 1965]. This angular spread has been confirmed by Rouscule et al. (this volume). The packet's group velocity, $v_{\text{group}}$, along $B_0$ is roughly $10^8$ cm/s. For completeness, we show in Figure 2b a three-dimensional display of $B = 2$ mG at $t = 0.4 \mu$s. The symmetry of the wave packet about $B_0$, expected from whistler propagation (i.e., within the resonance cone) as well as source symmetry, is very much in evidence.

For efficient radiation of whistlers, it is generally assumed that the source's dipole moment should be oriented perpendicular to $B_0$ in order to excite a wave with $k$ predominantly along $B_0$. We have found this not to be a necessary condition since the antenna excites equally well when oriented along (Figures 1 and 2) and across $B_0$ (not shown). The explanation is that it is the plasma response to the perturbation that allows for the excitation of whistler waves. In

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**Fig. 1.** Temporal evolution of one of the components of the perturbed magnetic field, $B_x \approx B_\theta$, at different axial distances, $z$, from a pulsed loop antenna with axis along $B_0$ (bottom trace is the externally measured current, $\Delta t = 0.1 \mu$s, $I_{\text{max}} = 0.1$ A). The traces show that the perturbation propagates dispersively since the packet front moves at a different speed than its middle.

**Fig. 2.** (a) Topology of $B_x \approx B_\theta$ in the $y-z$ plane ($x \approx 0$) at different times $t$ after applying a 0.1 $\mu$s current pulse to an insulated magnetic loop antenna whose normal is parallel to $B_0$. Image currents and their associated magnetic fields are induced which propagate in the whistler mode away from the exciter structure. (b) Constant magnitude surface of $B$ at 2 mG (at $t = 0.4 \mu$s) displaying the cylindrical symmetry of the wave packet consistent with whistler wave propagation.
the simplest term, it is Lenz's law. Nevertheless, it is instructive to see how physically this comes about. We offer a model for the mechanism in Figure 3 when the antenna's normal is parallel to \( B_0 \). Please note that the model applies to both sides while the figure discusses only one side of the antenna (\( z > 0 \)). As the current begins to flow in the loop, an oppositely directed, inductive electric field, \( E_i \), is imposed on the plasma (Figure 3a). This induces an \( E_i \times B_0 \) drift which produces a radial space charge imbalance. The excess charge is due to a shift of the electron population since the ions move along \( E_i \) during the time scale of the experiment (\( \tau_{ei} \gg \tau_{ce} \)). The space charge electric field, \( E_{sc} \), which has been experimentally confirmed by Stenzel et al. [1993], in turn drives the shielding current, \( J_0 = -neE_{sc}/B_0 \) (Figure 3b). This perturbation produces an opposite system further into the plasma which begets another one and so on (Figure 3b). The charge imbalances also lead to radial and axial currents as depicted in Figure 3c. Thus, a full three-dimensional magnetic field/current system carried by whistler waves is induced in the plasma. It is worth noting that such a model strongly depends on the orientation chosen as well as on the unmagnetized ions. Furthermore, there may be no waves that can carry the signals under other parameter regimes (e.g., \( \Delta t < 1/\omega_{pe} \)). Under those conditions, other mechanisms must be considered (see Stenzel et al. in this volume).

Because we cannot move the perturbation source or the plasma, we simulate the process by re-constructing their relative motion in space. The process is sketched in Figure 4 and has been discussed elsewhere in greater detail [Stenzel and Urrutia, 1990]. At \( n \) discrete points along the source trajectory, we assume that a packet was emitted at some time \( t = -n\delta t = -nD/v \), where \( v \) is the source velocity.

![Fig. 3. Model of whistler excitation by a pulsed loop antenna with normal parallel to \( B_0 \). (a) The inductive electric field due to \( \partial A/\partial t > 0 \) gives rise to a radial electron drift which, for unmagnetized ions, results in a space charge separation. (b) The space charge separation produces a radial electric field that drives Hall currents in the \( -\theta \) direction opposing the antenna's current. The inductive electric field of the image current then creates an opposing current system. (c) Parallel and transverse current system induced by image currents.](image)

![Fig. 4. Schematic diagram for the construction of whistler wings of a dc-magnetic field source moving with velocity \( v \perp B_0 \). A whistler packet is emitted at each position since the source resides in the flux tube of size \( D \) only for a short duration \( \delta t = D/v \). The superposition of wavelets forms a whistler wing that co-moves with the source. Motion along \( B_0 \) follows a similar construction.](image)
and \( D \) is the source extent along the direction of motion as well as the distance between discrete points. The data corresponding to that time is put into the volume surrounding this location. Owing to the wave propagation, each point in the volume can have contributions from different trajectory points. All contributions are then summed and the overall pattern is deduced. For motion across \( B_0 \), a structure resembling a wing results. Its inclination with respect to \( B_0 \) is given by \( \theta_{wing} = \tan^{-1}(v/v_{group}) \). It is important to note that the structure co-moves with the source which approximates a dc-driven antenna. Thus, the perturbed magnetic field pattern does not change in time relative to the loop and should not be considered a classical radiation pattern. Nevertheless, it is formed because the time rate of change of magnetic flux experienced by the plasma gives rise to the local excitation of whistler waves. This process is similar to the creation of eddy currents in a metal as a magnetic field source moves in its vicinity.

Figures 5a and 5b display the magnitude of the magnetic perturbation structures resulting from motion across and along \( B_0 \). For illustration purposes, a lower limit for \( B \) has been chosen (50 mG in 5a and 90 mG in 5b). The simulated speed of the source is \( v = 10^8 \) cm/s, comparable to the packet speed; hence, the inclination angle in Figure 5a is close to 45°. The location of the regions of maximum magnetic energy are not necessarily associated with the source location but are a result of constructive interference between the discrete steps employed in the simulation of the source motion. It must be kept in mind, however, that some spatial “aliasing” will take place since the discrete current is not a perfect square pulse. Furthermore, all effects due to the structures must be describable via linear superposition (e.g., the packet front should not modify the plasma parameters). The structures can then be analyzed to, for example, obtain the instantaneous directions of \( B(r) \) and \( J(r) \). A slow \((J^{-1} \gg \delta t = D_{source}/v_{source})\) modulation can also be applied to the antenna current to produce VLF waves. Such topics are, however, outside of the scope of this article.

**CONCLUSIONS**

The spatio-temporal evolution of the field of a pulsed magnetic loop antenna is measured over a large volume in a quiescent magnetoplasma. The fields are then computer-processed and the magnetic structure due to a moving, dc-driven magnetic loop antenna is obtained via the superposition of the single current pulse data. The results should be applicable to situations where the relative motion between a magnetic field source, such as Gaspra [Kivelson et al., 1993], and a magnetoplasma may produce whistler waves. Other possible applications are the interaction of spacecraft antennas with the solar wind or auroral arcs.

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**REFERENCES**


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