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# Whistler waves in space and laboratory plasmas

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**Abstract.** An overview of whistler wave phenomena in space and laboratory plasmas is given. Common features and different approaches between laboratory and space plasma research are pointed out. Both research activities have discovered a rich variety of whistler wave effects. Many useful applications have emerged. Open research topics and interactions between lab and space research on whistlers are pointed out.

## 1. Introduction

Whistler waves are possibly one of the first plasma waves observed. These waves have been studied for more than 100 years. A vast body of literature exists on whistlers and related phenomena in at least three areas: space plasmas, laboratory plasmas, and solid state physics. It is impossible to present a comprehensive review on this field in a short article. Instead of an in-depth review in any particular area, this article attempts to convey the large variety of whistler wave effects discovered by complementary methods in space and laboratory plasmas. In the spirit of the conference where this material was presented [Interrelationships Between Plasma Experiments in the Laboratory and Space (IPELS), Maui, Hawaii, June 23-27, 1997], this is an "interdisciplinary" review article which does not only focus on whistler phenomena in space plasmas. The latter has been thoroughly done in classical books [*Helliwell*, 1965], long review articles [*Al'pert*, 1980], and an abundance of topical reviews [*Helliwell*, 1988; *Sazhin et al.*, 1992; *Hayakawa*, 1992; *Sazhin and Hayakawa*, 1992; *Singh*, 1993; *Sazhin et al.*, 1993; *Sazhin and Hayakawa*, 1994; *Hayakawa*, 1995; *Sonwalkar*, 1995; *Johnstone*, 1996; *Singh et al.*, 1998].

There exist different terminologies for whistler waves in the space and laboratory communities. In space science, a "whistle" is specifically defined as an electromagnetic wave excited by lightning and dispersed while propagating through the ionosphere and magnetosphere. All other excitation mechanisms lead to "whistler-mode wave." Depending on their sound and spectrograms they are given many exotic names such as hiss, roar, saucers, chorus, risers, hooks, triggered emissions, etc.. In laboratory plasma physics any wave propagating in the whistler mode is simply called a "whistler wave." However, in bounded laboratory plasmas, in particular solid state plasmas, these waves are often called "helicons." Thus a reader from the space science community should simply interpret a laboratory whistler as any wave propagating in the whistler mode irrespective of its excitation mechanism.

Historically, whistler wave research started with passive ground observations of low-frequency radio waves from the ionosphere. Space plasma research blossomed in the era of spacecraft exploration. A wealth of whistler wave phenomena has been collected. Remote observations from ground, point measurements from space, and lack of parameter control have sometimes caused difficulties in explaining the observations uniquely. This lead to the desire to study whistlers in a controlled laboratory plasma. After the development of suitably large and collisionless laboratory plasmas and advanced plasma diagnostics many contributions on linear and nonlinear whistler waves were made in laboratory plasmas. Phenomena like resonance cones, beam-driven VLF hiss, filamentation instabilities, antenna properties, whistler wings, etc., added to the knowledge of whistler waves. The purpose of the present paper is to describe the major findings in both areas of whistler research so as to possibly stimulate new investigations. After a brief historic background, the following sections present whistler properties, major findings in space and laboratory plasmas, a section of emerging applications of whistler waves, and presently open questions for further research on whistlers.

## 2. Brief History

More than 100 years ago, *Preece* [1894] reported that operators on the Liverpool-Hamburg telephone lines heard strange rumbling sounds not produced by man. No explanation was given for these "Earth currents." Following the development of vacuum tube amplifiers, *Barkhausen* [1919] describes observations of "Pfeiftöne" (whistling tones) on long wire antennas and relates their occurrence to lightning, auroral activities, and wave dispersion. Such whistlers consist of electromagnetic signals which, after conversion to sound, produce falling tones from a few kHz downward, lasting up to several



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seconds. In the 1920s and 30s *Eckersley* [1935] pursued the research on "musical atmospherics," quantified the dispersion, and related the phenomenon to radiowave propagation in the ionosphere. The evolution of the magnetoionic theory [*Appleton*, 1932] produced a quantitative understanding for the dispersion of plane whistler waves in cold plasmas [*Storey*, 1953; *Ratcliffe*, 1959].

After World War II a nearly explosive growth started in whistler wave research. It was stimulated by (1) the era of satellites, enabling in situ observations in space, (2) the development of plasma sources, enabling controlled laboratory experiments, and (3) advanced theory and numerical simulations for whistler instabilities and nonlinearities. A vast body of knowledge on whistler modes has been accumulated and is continuing to grow because of ongoing basic research in all areas. n parallel, many interesting applications of whistler-mode waves are arising such as imaging subterranean structures [*Thiel et al.*, 1996], predictions of earthquakes and volcanic eruptions [*Hayakawa et al.*, 1993; *Molchanov et al.*, 1993], electron cyclotron and helicon plasma sources for industrial applications [*Stevens and Cecchi*, 1993; *Chen*, 1996], high power plasma switches [*Weber et al.*, 1996], directional whistler antennas, etc., to be described below.

## 3. Properties of Linear Whistler Modes

Whistler waves are electromagnetic waves in magnetized plasmas at frequencies below the electron Larmor frequency, $\omega \leq \omega_{ce}$, for electron plasma frequencies, $\omega_{pe} < \omega_{ce}$ and $\omega_{pe} > \omega_{ce}$. The low frequency limit of "electron" whistlers is the lower hybrid frequency, $\omega_{lh} \simeq (\omega_{ce}\omega_{ci})^{1/2}$. There are also "hydromagnetic" whistler modes in the range of the ion cyclotron frequency, $\omega_{ci}$ [*Russell et al.*, 1971; *Al'pert*, 1980]. Whistler modes are dispersive waves (group and phase velocities are frequency dependent), which can propagate oblique to the static magnetic field $\mathbf{B}_0$ up to a limiting "resonance cone" angle, given for electrons by $\theta_{phase,max} = \cos^{-1}(\omega/\omega_{ce})$. Near the oblique resonance the group and phase velocities are essentially orthogonal, and the wave energy is dominated by the electric field. For frequencies $\omega < \omega_{ce}/2$ there exists an oblique mode at $\theta_{phase} = \cos^{-1}(2\omega/\omega_{ce})$ with parallel group velocity called the Gendrin mode [*Gendrin*, 1961]. Along the direction of wave propagation ($\mathbf{k}$) the wave magnetic field is right-hand circularly polarized. The electric field of oblique whistlers has both space charge and inductive contributions, $\mathbf{E} = -\nabla\Phi - \partial\mathbf{A}/\partial t$. At an oblique density discontinuity the reflection of whistlers produces two reflected and one transmitted mode [*Lee*, 1969]. Refraction of whistlers in density nonuniformities has been studied carefully [*Smith*, 1961; *Helliwell*, 1965; *Walker*,1976] since it explains the remarkable ducting properties of whistlers. Ducting confines the wave energy in a field-aligned density crest or trough and allows oblique whistlers to propagate undamped over long distances along $\mathbf{B}_0$. All ground observations of whistlers, in particular the multiply reflected whistlers, involve ducting. Even narrow density troughs ($d < \lambda_{\parallel}$), requiring an eigenmode analysis [*Sodha and Tripathi*, 1977], exhibit remarkably good ducting properties [*Stenzel*, 1976b].

Plane whistler waves can decay because of electron collisions with neutrals and ions, because of collisionless electron cyclotron damping ($\omega - \omega_{ce} = \mathbf{k} \cdot \mathbf{v}_e$), and because of Landau damping for oblique modes ($\omega = \mathbf{k} \cdot \mathbf{v}_e$). The latter two mechanisms can also give rise to instabilities when the distribution function at the resonant velocity has a positive slope. The stability of whistlers in plasmas with non-Maxwellian distribution functions has been studied theoretically in detail [*Lee and Crawford*, 1970]. Nonlinear whistler phenomena will be described below in connection with observations.

## 4. Observations of Magnetospheric Whistlers and Whistler-Mode Waves

### 4.1. Ground-Based Measurements

The earliest and most common observations of whistlers are performed with long-wire antennas, amplifiers, and conversion to sound. The signals may be recorded and displayed as spectrograms such as the one shown in Figure 1 [*Potter*, 1951]. The observed whistlers are excited by natural lightning, couple through the Earth-ionospheric waveguide into an ionospheric duct, and undergo single or multiple reflections at conjugate points [*Smith*, 1961]. Ducted whistlers are observable for frequencies below half the minimum gyrofrequency along the $L$ shell determined by the observer's latitude [*Carpenter*, 1968]. Rarely, unducted whistlers are observed on the ground [*Sonwalkar*, 1995; *Ohta et al.*, 1997].

Although whistler wave propagation is firmly based on the theory of ducting, direct measurements of wave propagation in ducts cannot be performed from the

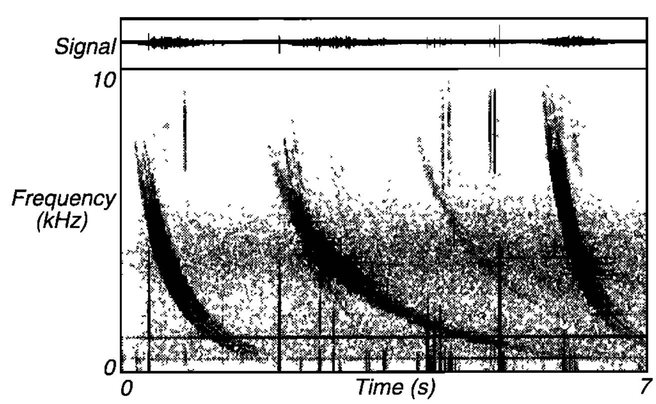


**Figure 1.** Typical spectrogram of ionospheric whistler waves observed on the ground. The (top) received waveform is Fourier analyzed and (bottom) displayed as an intensity plot vs frequency and real time. (Courtesy S. P. McGreevy, http://www-pw.physics.uiowa.edu/mcgreevy/, 1998).

ground. Properties of ducts have been indirectly obtained from optical emissions [*Hansen and Scourfield*, 1989] or from spacecraft data [*Sonwalkar et al.*, 1994c; *Strangeways*, 1986].

Passive observations of whistlers have been successfully used to obtain plasma parameters in the magnetosphere such as density, large-scale electric fields, and electron temperature [*Carpenter*, 1988; *Sazhin et al.*, 1992; *Singh et al.*, 1998]. Ion compositions are obtained from hydromagnetic whistlers (ion cyclotron waves) [*Russell et al.*, 1971; *Al'pert*, 1980; *Boskova and Jiricek*, 1986]. Whistler-mode waves have also been used to diagnose magnetic fields and particles in solar physics [*Mann and Baumgärtel*, 1989; *Chernov*, 1990].

Whistler wave-particle interactions are important processes which can lead to wave amplification and particle precipitation [*Kennel and Petschek*, 1966; *Melrose*, 1986]. Precipitation of energetic electrons into the lower ionosphere/atmosphere results in optical emissions [*Hansen and Scourfield*, 1989] and ionization phenomena which cause phase changes in subionospheric VLF waves [*Helliwell et al.*, 1973; *Inan et al.*, 1985; *Burgess and Inan*, 1993; *Strangeways*, 1996]. Ground observations are complemented by measurements from low-altitude satellites [*Voss et al.*, 1998]. Electron precipitations can also be triggered by active stimulation experiments with ground-based high-power VLF (3-30kHz) transmitters discussed below.

### 4.2. Observations From Satellites

Whistlers are readily detected with electric and magnetic antennas on spacecraft. As on the ground, only frequency spectra are recorded while wave vectors are inferred [*Sakamoto et al.*, 1995], radiation sources are extrapolated from direction-finding techniques [*Hayakawa et al.*, 1990] and ray-tracing models [*Nagano et al.*, 1998]. In situ measurements are sensitive to the entire spectrum of oblique whistlers ($\omega < \omega_{ce} \cos\theta$), hence most of the observed whistlers are oblique, unducted, magnetospherically reflected (MR) waves. Ducted whistlers are rarely observed on satellites [*Thomson and Dowden*, 1977; *Sonwalkar et al.*, 1994c]. Few whistlers are observed in the outer magnetosphere [*Koons*, 1985; *Nagano et al.*, 1998]. Lightning excites whistlers not only in Earth's magnetosphere but also on Jupiter [*Hobara et al.*, 1995], Neptune [*Gurnett et al.*, 1990; *Gurnett and Kurth*, 1995], and on Venus [*Scarf*, 1985], although the latter observations are still being debated [*Cole and Hoegy*, 1997; *Strangeway*, 1997].

The ionosphere/magnetosphere produces various plasma instabilities which lead to the emission of waves propagating in the whistler branch. Most of these instabilities are due to anisotropic electron distributions such as beams, loss cones, rings, and temperature anisotropies. In the auroral zone, VLF hiss is generated by energetic electrons [*Cornilleau-Wehrlin et al.*, 1993], explained by mechanisms such as Cherenkov and cyclotron instabilities [*Gurnett and Frank*, 1972; *Maggs*, 1989], and recently reviewed by *Sazhin et al.* [1993]. VLF emissions can also propagate to and be studied on the ground [*Sazhin and Hayakawa*, 1994]. Whistler-mode emissions are also produced in the bow-shock region of Earth [*Hayashi et al.*, 1994] and of various other planets [*Orlowski and Russell*, 1995], in the solar wind [*Gary et al.*, 1994], in radiation belts [*Coroniti et al.*, 1987], by proton beams [*Wong and Goldstein*, 1987], and by pick-up ions [*Tsurutani et al.*, 199]. Whistler emissions are also triggered by lightning-generated whistlers [*Nakamura and Ohdoh*, 1989; *Sonwalkar and Inan*, 1989] and man-made whistler-mode waves [*Helliwell and Katsufrakis*, 1974; *Mielke et al.*, 1992]. Other sources of natural and man-made whistler-mode waves detected in space are emissions linked to seismic activity [*Molchanov et al.*, 1993; *Parrot*, 1995; *Chmyrev et al.*, 1997], nuclear explosions [*Helliwell*, 1965], power line harmonic radiation [*Helliwell et al.*, 1975; *Bullough*, 1995; *Parrot and Zaslavski*, 1996], and active wave injection experiments discussed below.

### 4.3. Active Experiments With Whistler-Mode Waves

Man-made excitation of whistler-mode waves in the ionosphere have been performed with high-power VLF transmitters from ground stations [*Helliwell et al.*, 1964]. In transmission experiments between conjugate points, not only the applied wave is observed but also triggered emissions with larger intensities and different frequencies[*Mielke et al.*, 1992]. Free energy in anisotropic electron distributions is thought to be released by the injected wave in the form of VLF emissions and electron precipitation [*Kennel and Petschek*, 1966; *Winglee*, 1985; *Molvig et al.*, 1988; *Johnstone*, 1996]. The injected wave signals observed on satellites have shown spectral broadening and sidebands [*Bell et al.*, 1983; *Tanaka et al.*, 1987]. These have been explained by both linear [*Bell and Ngo*, 1990] and nonlinear wave-wave interactions, for example, parametric instabilities [*Chian*, 1996] and trapped particle instabilities [*Denavit and Sudan*, 1975].

With strong HF transmitters on the ground, VLF waves have been generated during ionospheric modification experiments [*Belyaev et al.*, 1987; *Rowland et al.*, 1996; *Barr and Stubbe*, 1997]. The principle is based on a controlled modulation of the electrojet current by changing the plasma conductivity through electron heating with a modulated HF wave. The more efficient direct excitation of VLF waves from spacecraft has not yet been successful because of difficulties of deploying large loop antennas [*Sonwalkar et al.*, 1994a] or long tethers in space [*Stone and Bonifazi*, 1998]. Earlier experiments with powerful HF topside sounders showed the nonlinear excitation of lower-hybrid waves [*Benson and Vinas*, 1988].

Whistler-mode waves have been generated during the injection of electron beams from rockets [*Winckler et *al.*, 1984; *Gringuaz et al.*, 1985; *Kellogg et al.*, 1986] and spacecraft [*Reeves et al.*,1990], as reviewed by *Neubert and Banks* [1992]. Analysis [*Farrell et al.*, 1988; *Wong and Lin*, 1990] and numerical simulations [*Nishikawa et al.*, 1989] indicate that the waves are mainly generated by coherent Cherenkov instabilities as earlier demonstrated in the laboratory [*Stenzel*, 1977].

## 5. Laboratory Experiments on Whistlers

### 5.1. Early Experiments

One of the first identifications of whistler waves in laboratory plasmas was reported on ZETA, a toroidal pinch plasma for early fusion experiments [*Gallet et al.*, 1960]. The transmission of microwave signals ($\omega < \omega_{ce} < \omega_{pe}$) between two fixed antennas was shown to be field-aligned, as predicted for parallel whistlers. Further transmission experiments were performed in linear discharge plasmas including phase measurements to infer the dispersion relation [*Mahaffey*, 1963; *Dellis and Weaver*, 1964; *Bachynski and Gibbs*, 1966]. Similar phase shift measurements were employed in solid state physics to demonstrated the existence of helicon waves in semiconductors [*Furdyna*, 1965]. However, in contrast to solids, the receiving antennas can be moved through a gaseous plasmas so as to record the local phase and amplitude. Interferometry with movable antennas was developed, which allowed direct measurements of wavelengths, hence the dispersion relation $\omega(\mathbf{k})$. Wave damping due to collisions and cyclotron damping were investigated [*McVey and Scharer*, 1974; *Ohkubo and Tanaka*, 1976; *Barrett*, 1986]. Propagation of wave packets yielded the group velocity [*Baker and Hall*, 1974]. Since antenna-launched waves are not plane waves and the plasmas were not infinite and uniform, corrections for finite-sized geometries were required [*Lee*, 1969; *Ohkubo et al.*, 1971; *Uhm et al.*, 1988].

Early interferometry was performed by moving a receiving antenna along a line, for example, parallel to $\mathbf{B}_0$. Subsequently, the measurements were extended to two dimensions by scanning over a plane and finally were extended to a three-dimensional (3-D) volume. An example of such 3-D data is displayed in Figure 2 [*Rousculp et al.*, 1995]. The spatial amplitude distribution of the magnetic field, $B(x, y, z, t = \text{const})$, of a whistler wave packet excited by a current pulse in a magnetic loop antenna is shown in Figure 2a. In time, the wave packet propagates dispersively along $\mathbf{B}_0$. Figure 2b shows a 3-D Fourier transform of the wave field in $\mathbf{k}$ space at a given frequency, $B(k_x, k_y, k_z, \omega = \text{const})$. The eigenmodes of the wavepacket lie close to the theoretical whistler dispersion surface $\omega(\mathbf{k})$ indicated by a 3-D grid. The loop antenna with its axis along $\mathbf{B}_0$ excites only oblique whistlers. Since multipoint measurements have not been performed, such 3-D data is unavailable for space plasmas. In space, $\mathbf{k}$ vectors are calculated

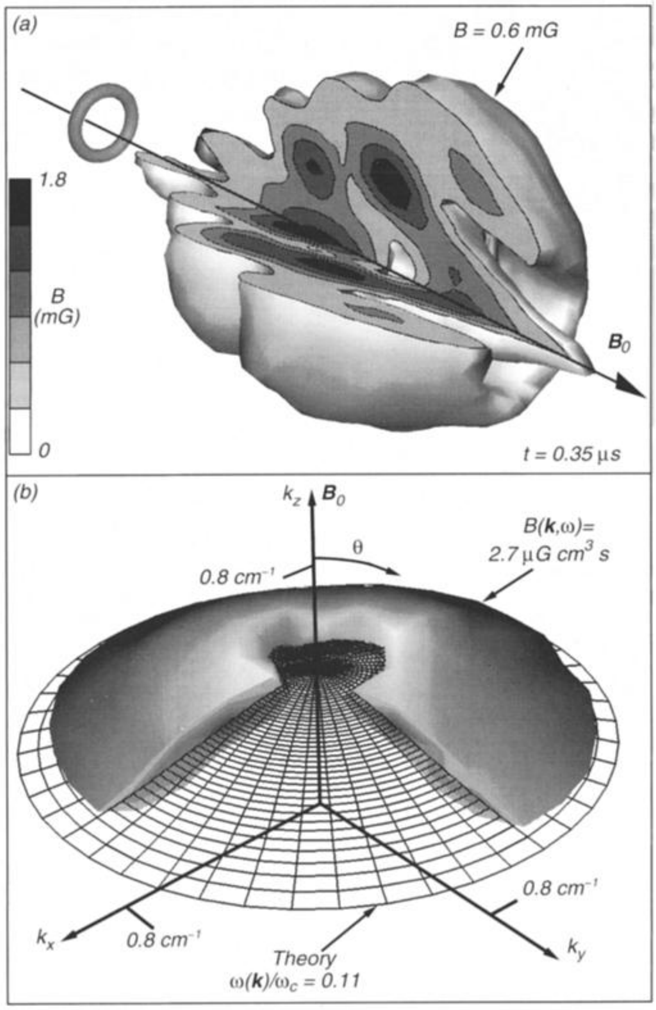


**Figure 2.** Whistler wave pulse excited with a loop antenna in a uniform laboratory plasma. (a) Instantaneous amplitude distribution of the wave magnetic field in three dimensional real space, $(B_x^2 + B_y^2 + B_z^2)^{1/2}(x, y, z, t = \text{const})$. (b) Fourier components of the wave field in 3-D $\mathbf{k}$ space, $B(k_x, k_y, k_z, \omega = \text{const})$. The grid represents the theoretical dispersion surface of whistlers. These data illustrate present multipoint ($> 10^4$) measurements in laboratory plasmas [*Rousculp et al.*, 1995].

from electric and magnetic field measurements assuming plane waves and the validity of the dispersion relation [*Sonwalkar and Inan*, 1986; *Ladreiter et al.*, 1995; *Sakamoto et al.*, 1995]. Vice versa, whistler spectrograms are not common in laboratory plasmas although the waveform of a nose whistler can be readily demonstrated [*Stenzel*, 1976a].

### 5.2. Resonance Cones, Antennas, and Ducting

At a given frequency, the whistler wave dispersion predicts a continuum of modes with wave vectors $\mathbf{k}_{\parallel} < \mathbf{k} < \infty$. These can be excited by antennas where the amplitude and phase of the eigenmodes depend on the shape of the antenna. For a "point radiator," both theory and observations show that the field amplitude assumes a maximum along a resonance cone of angle $\theta_{group,max} = \pi/2 - \theta_{phase,max} \simeq \sin^{-1}(\omega/\omega_{ce})$ [*Fisher and Gould*, 1971]. These cones have been observed for short electric and magnetic dipoles in both the near zone and the far zone ($r > \lambda$) [*Boswell and Gonfalone*, 1975; *Stenzel*, 1976c]. Resonance cones also exist in the frequency regime $\omega_{ce} < \omega < (\omega_{pe}^2 + \omega_{ce}^2)^{1/2}$, which is of interest for density diagnostics. Fine structure due to warm plasma modes can be used to obtain the electron temperature [*Muldrew and Gonfalone*, 1974]. These laboratory observations have stimulated diagnostic applications in ionospheric plasmas [*Gonfalone*, 1974; *Rohde et al.*, 1993].

Since antennas in plasmas are essential for wave excitation and detection, their properties have been extensively studied in laboratory and space plasmas [*Balmain*, 1972]. Radiation patterns of VLF antennas have been calculated [*GiaRusso and Bergeson*, 1970; *Wang and Bell*, 1972]. Impedance measurements have been performed in space [*Koons and McPherson*, 1974], but in the absence of multipoint measurements in space, radiation patterns of loops are only obtained in large laboratory plasmas [*Stenzel*, 1976a]. Recent experiments with loop antennas in a uniform plasma obtain the whistler wave fields, $\mathbf{B}(\mathbf{r},t)$, in three dimensions and time [*Rousculp et al.*, 1995]. Subsequent Fourier transformation in space and time, $\mathbf{B}(\mathbf{k},\omega)$, reveals a spectrum of oblique eigenmodes satisfying the theoretical dispersion relation for plane whistler modes, $\omega(\mathbf{k})$. The frequency-dependent radiation resistance has been determined from the Poyntings vector and antenna current, a method preferrable over measurements of the driving point impedance since the latter includes nonradiative absorption processes.

With receiving loop antennas, the thermal noise of whistler waves has been measured in a Maxwellian plasma [*Golubyatnikov and Stenzel*, 1993]. The observed $1/f$ spectrum, shown in Figure 3, consists of oblique whistlers produced by incoherent Cherenkov radiation of tail electrons. In the presence of energetic, high pitch angle electrons the magnetic fluctuation spectrum peaks at harmonics of the electron cyclotron frequency, [*Stenzel and Golubyatnikov*, 1993], which has also been observed in active experiments in space [*Gough et al.*, 1998].

Laboratory experiments have demonstrated that the sign of the magnetic helicity in whistler wave packets depends on the direction of wave propagation with respect to the dc field. Novel directional antennas based on helicity injection have been developed [*Rousculp and Stenzel*, 1997] as will be discussed further below.

Sheaths surrounding electric antennas are a well-known source for nonlinear effects, which can give rise to rectification [*Takayama et al.*, 1960], parametric instabilities [*Stenzel et al.*, 1975], transit-time instabilities [*Stenzel*, 1989], and frequency mixing, a topic relevant to but rarely discussed in space plasmas [*Boehm et al.*, 1994]. For magnetic loop antennas, nonlinearities arise from the $\mathbf{v}(B) \times \mathbf{B}$ term, which generates harmonics and dc magnetic fields [*Stenzel and Urrutia*, 1998a]. Nonlinear whistlers with wave magnetic fields comparable to the ambient field have been generated in high-beta laboratory plasmas, a topic of interest to the study of whistlers on Venus [*Cole and Hoegy*, 1997].

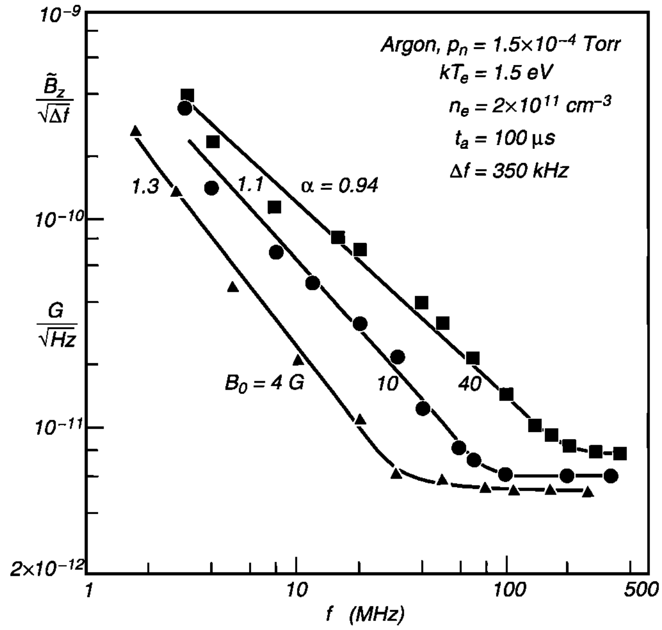


**Figure 3.** Thermal magnetic noise in a Maxwellian afterglow plasma in the range of whistler waves. The $1/f$ spectrum consists of Cherenkov-excited oblique whistlers. The flat spectrum above $\omega_{ce}$ is due to shot noise. Note the high sensitivity of magnetic measurements ($\sim 10^{-13}T$) [*Golubyatnikov and Stenzel*, 1993].

Because of the difficulty of deploying long wire antennas (tethers, loops) in space, it has been suggested to use modulated particle beams as antennas [*Harker and Banks*, 1985; *Kotsarenko et al.*, 1988]. Such ideas have been tested both in laboratory and space plasmas [*Neubert and Banks*, 1992]. In a laboratory plasma a field-aligned, modulated ($\omega < \omega_{ce}$), resonant ($v_{beam} = \omega/k_{\|}$) electron beam is observed to linearly excite whistler waves [*Krafft et al.*, 1994; *Kostrov et*, 1998a]. Perpendicular injection of an energetic modulated electron beam excites whistlers like a magnetic loop antenna [*Griskey et al.*, 1997]. However, the coherence of these "beam antennas" is limited by velocity spread caused by rapidly growing high frequency beam-plasma instabilities.

With the development of large-diameter (up to 1 m) cathodes [*Stenzel and Daley*, 1980] it was possible to generate large, dense, uniform, magnetized discharge plasmas of high quality. With antennas movable in three dimensions through the plasma, it became possible to do ray-tracing measurements. The propagation of antenna-launched whistlers in uniform and nonuniform plasmas has been measured, demonstrating linear ducting [*Stenzel*, 1976a; *Sugai and Takeda*, 1980], mode conversion [*Bamber et al.*, 1995; *Rosenberg and Gekelman*, 1998], the Gendrin mode [*Stenzel*, 1976a], and efficient ducting in density troughs narrower than a parallel wavelength [*Stenzel*, 1976b; *Sugai et al.*, 1979]. Since wave propagation in ducts cannot be mapped with a spacecraft, these laboratory experiments should be of great interest to the space community interested in the leakage of whistlers from narrow ducts [*Strangeways*, 1986; *Kaufman*, 1986; *Karpman*, 1997], duct size [*Hansen and Scourfield*, 1989; *Sonwalkar et al.*, 1994c], and duct formation [*Rodger et al.*, 1998].

### 5.3. Whistler Instabilities (Velocity Space, Parametric, and Modulational)

Whistler waves can be driven unstable by wave-particle interactions involving Cherenkov and cyclotron resonances. The former has been demonstrated in a large beam-plasma laboratory device [*Stenzel*, 1977]. The beam generates broadband whistler wave noise, which, by two-dimensional (2-D) correlation techniques, is found to consist of oblique whistlers near the resonance cone whose parallel phase velocity matches the beam velocity ($\omega/k_{\|} \simeq v_{beam}$) . The Cherenkov instability is further clarified by amplifying a test whistler wave launched from a small antenna. The one-dimensional (1-D) interferometer trace of Figure 4a shows the growth of the test wave along the beam, satisfying wave-particle resonance, $\omega/k_{\|} = v_{beam}$. Two dimensional interferometry shows the phase fronts (Figure 4b) and amplitude contours (Figure 4c). These measurements show that in the half space along the beam the wave grows in the direction of the group velocity cone, $\sin\theta_{group} \simeq \omega/\omega_{ce}$, nearly orthogonal to the phase velocity cone of angle $\cos\theta_{phase} \simeq \omega/\omega_{ce}$. In the opposite hemisphere, the wave decays along the resonance cone as without a beam. The instability saturates by beam broadening. Such laboratory experiments demonstrate clearly the physics of the Cherenkov instability which is discussed but not experimentally proven for VLF hiss and electron beam injection experiments.

Loss cone distributions and temperature anisotropies ($T_\perp > T_{\|}$) can produce whistler instabilities [*Litwin and Sudan*, 1986] , which have been observed in a magnetic mirror device with RF heating at the electron cyclotron frequency [*Garner et al.*, 1987]. In a high-beta plasma an anisotropic tail of electrons creates a new unstable electromagnetic mode [*Urrutia and Stenzel*, 1984], which has been explained theoretically and related to space plasmas [*Goldman and Newman*, 1987].

Parametric instabilities of whistlers have probably received more attention in theory [*Trakhtengerts*, 1973; *Berger and Perkins*, 1976; *Lee and Kuo*, 1984; *Chian et al.*, 1994] than in experiments [*Boswell and Giles*, 1976]. *Boswell and Giles* [1976] observed the trapping of whistler decay waves along the resonance cone where convective losses are at a minimum ($v_{group} \to 0$). In the ionosphere the decay of whistler waves into lower hybrid

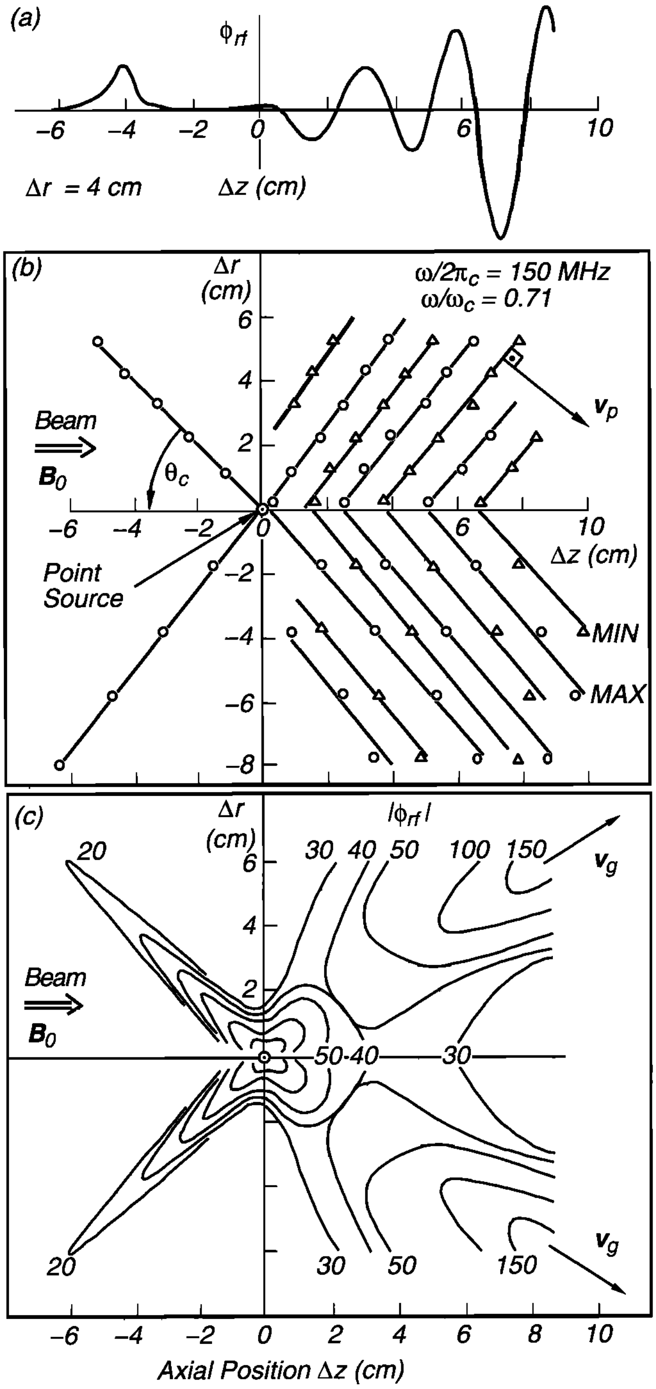


**Figure 4.** Cherenkov instability of whistlers in a large beam-plasma system: (a) 1-D interferometer trace of a test wave from a point source showing wave growth along the beam and a resonance cone peak opposite to the beam, (b) 2-D phase fronts showing oblique phase velocity of unstable whistlers close to the limiting angle of propagation, $\cos\theta_{phase} \simeq \omega/\omega_{ce}$, and (c) 2-D amplitude contours showing oblique wave growth close to the group velocity resonance cone angle, $\sin\theta_{group} \simeq \omega/\omega_{ce}$ [*Stenzel*, 1977].

and kinetic Alfvén waves has been analyzed [*Yukhimuk and Roussel-Dupree*, 1997] so as to explain observations of lightning-excited wave spectra [*Kelley et al.*, 1990; *Bell et al.*, 1994]. Three-wave interactions between an electromagnetic pump and decay whistler and lower hybrid waves have also been investigated in laser-plasma interactions [*Mourenas*, 1997]. The interaction of Langmuir waves and whistlers can produce the observed filamentary fine structure of solar type IV radio bursts [*Fomichev and Fainshtein*, 1988].

Modulational instabilities arise when a whistler wave modifies those plasma parameters which affect its dispersion and thereby modifies its propagation and amplitude. Most common are density modifications via the ponderomotive force, thermal pressure, and ionization, which can lead to self-focusing and filamentation instabilities [*Washimi*, 1973; *Sodha and Tripathi*, 1977; *Karpman*, 1992]. Initial observations of thermal self-focusing of whistlers were reported by *Litvak* [1974]. Channeling by self-ionization has been reported by *Vdovichenko et al.* [1986]. A detailed experiment on "self-ducting" of whistlers was performed in a large uniform laboratory plasma [*Stenzel*, 1976b]. A large-amplitude whistler wave was observed to generate a field-aligned density depression in which the wave became ducted. As shown in Figure 5, nearly perfect ducting occurred in density depressions as narrow as the wavelength. Later experiments found that the density trough was produced by electron heating in the antenna near-zone [*Sugai et al.*, 1978] and that the efficient wave trapping involved reflections of quasi-electrostatic whistlers in the duct [*Golubyatnikov et al.*, 1989; *Kostrov et al.*, 1998b]. These nonlinear phenomena studied in the laboratory have stimulated new ideas for more efficient VLF antennas on spacecraft [*Zaboronkova et al.*, 1996].

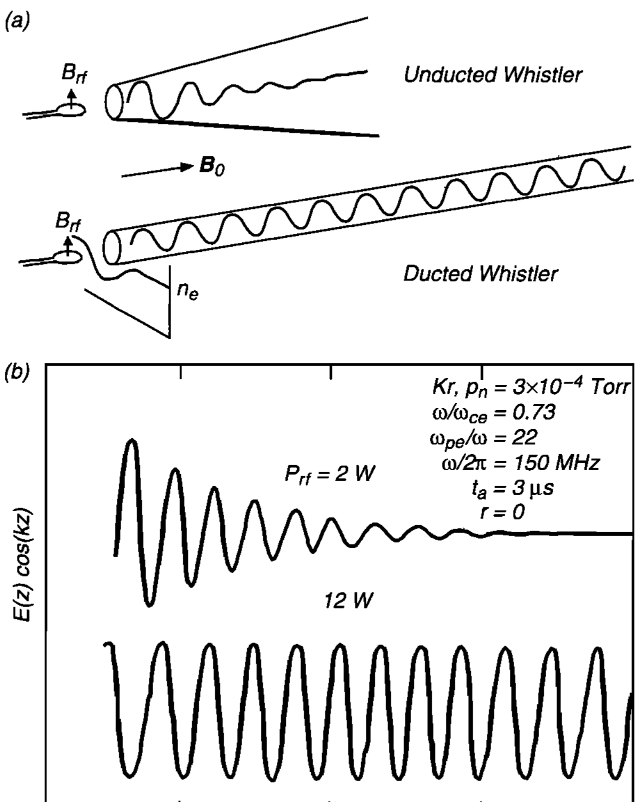


**Figure 5.** Filamentation of whistlers in a laboratory plasma. (a) Schematic diagram showing that a small-amplitude antenna-launched whistler exhibits an amplitude decay because of geometric wave spread while a strong whistler produces a field-aligned density trough in which it becomes trapped. The duct can be narrower than the parallel wavelength. (b) Measured ducted and unducted whistlers in a laboratory plasma [*Stenzel*, 1976b].

Density modifications by the ponderomotive force have been investigated for oblique whistlers above the lower hybrid frequency [*Stenzel and Gekelman*, 1977]. Using a circular line source, a converging resonance cone produced at its focus a wave pressure far in excess of the particle pressure. Time-resolved measurements of the pulsed experiment showed the formation of a deep density depression at the focus, the deformation of the resonance cone fields, a partial density recovery, and repetition of the nonlinear interaction. Ion acceleration via space charge fields dominated over parallel electron acceleration. These observations are related to the physics of lower hybrid solitons [*Seyler*, 1994] and present no questions about particle conservation [*Robinson et al.*, 1996].

In collisional plasmas, a modulational instability can arise from the temperature dependence of the plasma conductivity. Fast electron heating and parallel heat conduction is observed to form a field-aligned channel of high Spitzer conductivity in a cold uniform magnetoplasma [*Urrutia and Stenzel*, 1991]. The intense whistler wave propagates predominantly in its self-generated collisionless channel while low-amplitude whistlers are collisionally damped. No ducting by density gradients is involved in this filamentation process.

### 5.4. Whistlers in Electron MHD (Transient Currents, Helicity, and Whistler Wings)

While many wave phenomena are thought of in terms of plane monochromatic eigenmodes, a vast class of whistler phenomena arise in the form of temporal transients and spatially bounded phenomena, i.e., wave packets. Such transient phenomena are common in electron magnetohydrodynamicss (EMHD) physics [*Kingsep et al.*, 1990]. In contrast to ordinary MHD where the plasma behaves like a single magnetized fluid, in EMHD only the electrons are magnetized while the ions are not. This arises on timescales $f_{ce}^{-1} < t < f_{ci}^{-1}$ and spatial scales $r_{ce}^{-1} < r < r_{ci}^{-1}$. The transition regime has been called Hall MHD [*Huba*, 1995]. A basic initial and boundary value problem is the penetration of transient currents or magnetic fields into ideal plasmas, which is a solution to the differential equation describing frozen-in fields, $\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B})$. In MHD, the transient processes can be decomposed into Alfvén eigenmodes; in EMHD they can be decomposed into low-frequency whistler modes. For propagation along the ambient field, Fourier analysis of the differential equation yields the whistler dispersion relation, $\omega = \omega_{ce}(kc/\omega_{pe})^2$. In EMHD the fluid velocity is given by the Hall effect, $\mathbf{v} = \mathbf{v}_e = -\mathbf{J}/ne \simeq \mathbf{E} \times \mathbf{B}_0/B_0^2$. For small perturbations, $\mathbf{B} \ll \mathbf{B}_0$, propagating along $\mathbf{B}_0$, the evolution equation predicts that the current density is parallel to the wave magnetic field, $\mathbf{J} = \pm\sigma_{\mathrm{H}} v_{\|}\mathbf{B}$, where $\sigma_{\mathrm{H}} = ne/B_0 = J/E$ is the Hall "conductivity" and $v_{\|} = E/B$ is the propagation velocity. Fields with $\mathbf{J} \parallel \mathbf{B} \parallel \mathbf{A}$ exhibit helicity, defined as $H = \int \mathbf{A} \cdot (\nabla \times \mathbf{A})\, dV$, which implies vortex topologies with linked, knotted, or twisted field lines [*Moffat*, 1978; *Berger and Field*, 1984; *Isichenko and Marnachev*, 1987]. Conservation of helicity and energy are of interest in both MHD and EMHD [*Taylor*, 1974]. Force-free electromagnetic fields exist in EMHD [*Osherovich and Gliner*, 1988; *Stenzel and Urrutia*, 1990a]. When the electron inertia is retained in Ohm's law, the generalized vorticity, $\mathbf{\Omega} = \nabla \times \mathbf{v}_e - e\mathbf{B}/m_e$, rather than the magnetic field $\mathbf{B}$ is frozen into the electron fuid, $\partial\mathbf{\Omega}/\partial t = \nabla \times (\mathbf{v}_e \times \mathbf{\Omega})$ [*Yankov*, 1995; *Urrutia and Stenzel*, 1996].

Near magnetic null points, MHD changes to EMHD as the ion Larmor radius becomes larger than the magnetic field gradient scale length. Reconnection of thin current sheets ($c/\omega_{pe} < r < r_{ci}$) is governed by EMHD physics [*Bulanov et al.*, 1992; *Drake et al.*, 1994; *Biskamp et al.*, 1997; *Avinash et al.*, 1998]. The motion of small conducting bodies and magnets through space plasmas generates magnetic perturbations in the form of a Cherenkov cone, named "whistler wing" [*Stenzel and Urrutia*, 1989; *Kivelson et al.*, 1993; *Gurnett*, 1995; *Wang and Kivelson*, 1996; *Thomson et al.*, 1996]. Hall and electron MHD physics also apply to the rapid penetration of magnetic fields during barium releases in space [*Huba et al.*, 1992], plasma beams [*Armale and Rostoker*, 1996], and plasma-opening switches in the laboratory [*Weber et al.*, 1995].

Detailed laboratory experiments have shown that under EMHD conditions, pulsed currents are transported in the whistler mode [*Urrutia and Stenzel*, 1988 and 1997]. Typically, a step function or pulsed voltage is applied to an electrode, and the perturbed magnetic field is measured in three-dimensional space and time. Fourier analysis shows that the eigenmodes fall on the dispersion surface of oblique whistlers, $\omega(\mathbf{k}) = \mathrm{const}$. The current density is obtained from Ampère's law, $\mathbf{J}(\mathbf{r}, t) = \nabla \times \mathbf{B}/\mu_0$. The current lines are usually helical because of the linkage of field-aligned and Hall currents. At the current front, the current density lines spiral back to the return electrode, satisfying current closure at all times. As shown in Figure 6, an applied current step evolves into a long flux rope. Figure 7 demonstrates that a short current pulse detaches from the electrode and propagates as nearly spherical vortex along $\mathbf{B}_0$. Its helicity is positive (negative) for propagation along (against) $\mathbf{B}_0$. Reflections reverse the sign of the helicity. Collisional damping decreases magnetic helicity and energy at the same rate; however, the topological property, $\mathbf{A} \parallel \mathbf{B} \parallel \mathbf{J}$, remains unchanged. Dispersion causes a spherical vortex to elongate into a conical shape. Weaker secondary vortices of opposite $\mathbf{J}$, $\mathbf{B}$ but same helicity are induced.

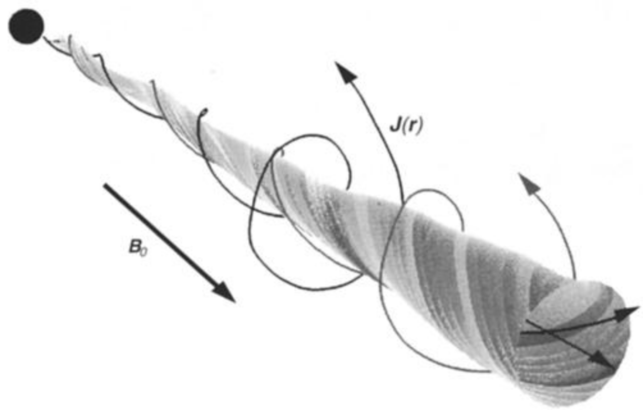


**Figure 6.** Measured current density lines, $\mathbf{J}(\mathbf{r}, t = \mathrm{const})$, and surface of a current tube ($I = \mathrm{const}$) for a pulsed current from an electrode in a magnetoplasma. The flux-rope topology arises from the superposition of an electron Hall current and the field-aligned current. In electron MHD the current front propagates at the speed of a whistler wave [*Urrutia and Stenzel*, 1997].

The helicity properties of whistler wave packets are not only of scientific interest but can lead to new applications such as directional antennas. As schematically shown in Figure 8, a simple magnetic or electric dipole antenna excites wave packets of opposite helicity propagating in $\pm\mathbf{B}_0$ direction. Since no helicity is injected, no net helicity is found in the plasma, which is consistent with helicity conservation. Helicity injection with linked or knotted antennas implies asymmetric radiation [*Rousculp and Stenzel*, 1997]. The sign of the injected helicity determines the direction of wave propagation. A positive-helicity antenna excites vortices along $\mathbf{B}_0$ but receives them from the opposite direction; hence transmission is nonreciprocal. A linked torus-loop antenna has been found to have excellent directionality (> 20 dB). Measurements of its wave fields are shown in Figure 9. Figures 9a and b show the vortex topology as displayed by the linked fields $B_\theta$ and $B_z$. Figure 9c demonstrates that the wave amplitude is much larger for propagation along $\mathbf{B}_0$ than opposite to $\mathbf{B}_0$. Wave propagation of $B_z(z, t)$ is shown in Figure 10 for a sinusoidal antenna current, $I(t)$. The wave amplitudes in $\pm z$ direction differ by almost an order of magnitude. The direction of preferred radiation is reversed by a simple sign change of either the toroidal or solenoidal current.

The motion of a conducting and/or magnetic object in a magnetoplasma induces time-dependent plasma currents. These may fall into the EMHD regime when the transit time across the field is short compared to an ion cyclotron period. Examples in space are electrodynamic tethers in the ionosphere [*Dobrowolny and Melchioni*, 1993; *Stone and Bonifazi*, 1998] and aster-

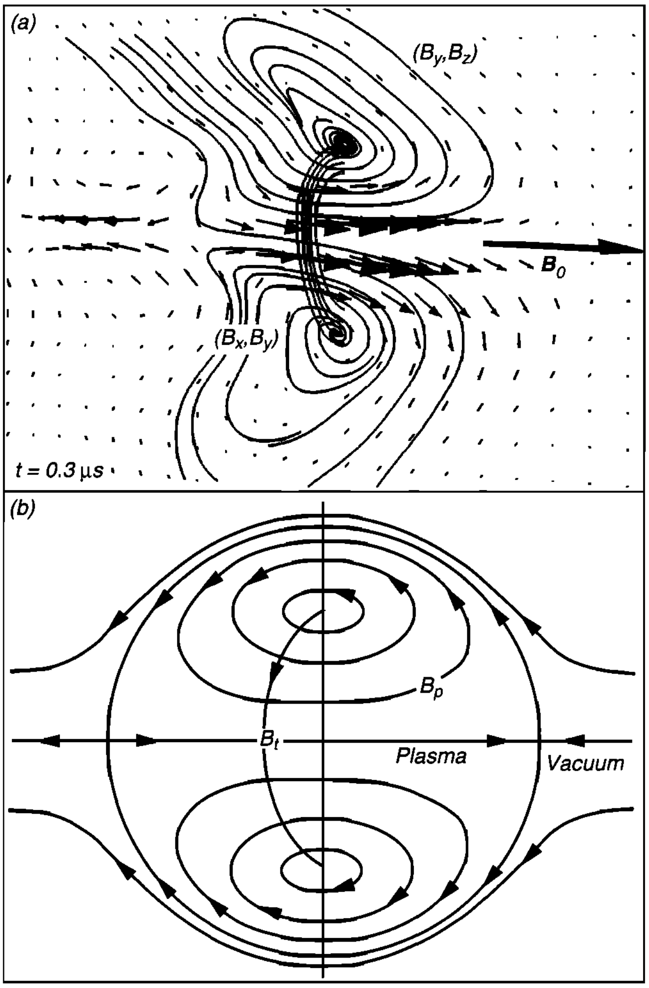


**Figure 7.** The excitation of a short current pulse in a magnetoplasma produces a magnetic field of vortex topology: (a) measurement, and (b) model of a spherical vortex. The vortex propagates in the whistler mode, is force-free, and has positive/negative helicity for propagation along/opposite to $\mathbf{B}_0$ [*Stenzel and Urrutia*, 1990a].

oids in the solar wind [*Kivelson et al.*, 1993; *Baumgärtel et al.*, 1994; *Gurnett*, 1995; *Wang and Kivelson*, 1996]. The current path and closure of tethered satellites has been addressed in a laboratory experiment [*Stenzel and Urrutia*, 1990b; *Urrutia et al.*, 1994a; *Stenzel and Urrutia*, 1998b]. An electron-emitting electrode has been tethered across $\mathbf{B}_0$ to an electron collector and energized by a current pulse of duration given by velocity and electrode dimension, $\Delta t \simeq d/v_\perp$. The space-time dependence of the transient current pulse has been measured. A snapshot of the observed current density lines is presented in Figure 11. One can identify a primary current loop consisting of the tether current, two field-aligned current channels from the electrodes, and a cross-field Hall current induced by the insulated tether wire. The primary loop induces a multitude of secondary loops of opposite polarity and decreasing strength in the plasma. These are manifestations of the dispersion of a whistler wave packet. In time, as the tether current is switched off, all current loops close within the plasma as they propagate away from the exciter in the whistler mode. In order to obtain the fields of a moving dc source, many delayed current pulses, excited from displaced tether positions, are superimposed as by Huygen's principle to form a wavefront. Similar to a ship's wake, a coherent electromagnetic perturbation, termed a whistler wing, was observed [*Stenzel and Urrutia*, 1989]. Both the tether wire and the two end electrodes, i.e., the entire dipole, radiate coherent whistler wave packets when they move across $\mathbf{B}_0$. Because of the whistler dispersion and oblique propagation, the wings are broadening with distance from the source. Thus the current path ($\mathbf{J} \parallel \mathbf{B}_{wave}$) does not form a simple field-aligned loop into the ionosphere as predicted by earlier MHD models [*Banks et al.*, 1981]. Subsequent theories and numerical simulations have confirmed the relevance of whistler wings to tethers and ionospheric current modulations [*Wilson et al.*, 1996; *Zhou et al.*, 1996;; *Papadopoulos et al.*, 1994].

The results of whistler wings from an electric dipole have been extended to that of a magnetic dipole [*Urrutia et al.*, 1994b]. Measuring the pulse response from a loop antenna, the whistler wake of a dc dipole moving across and along $\mathbf{B}_0$ have been constructed. Figure 12 shows an example of a whistler wing from a dc magnetic dipole moving across $\mathbf{B}_0$ or, vice versa, a stationary

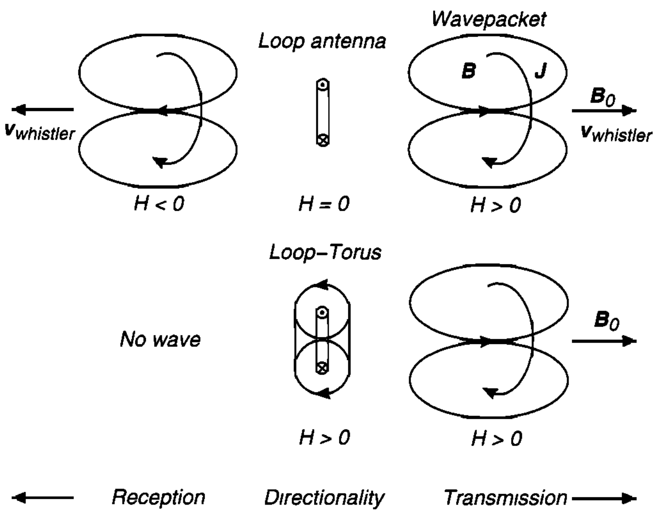


**Figure 8.** Schematic diagram explaining antenna directionality by helicity conservation. A simple field-aligned loop antenna possessing no helicity excites two equal whistler vortices of opposite helicity propagating in $\pm\mathbf{B}_0$ direction; hence zero helicity is maintained. An antenna consisting of a loop along the axis of a torus produces helical fields. For positive-helicity injection a vortex of positive helicity, i.e., propagating in $+\mathbf{B}_0$ direction, is excited. Its directionality is reversed as a receiving antenna, its directionality is reversed. Transmission between two identical antennas is unidirectional, i.e., nonreciprocal.

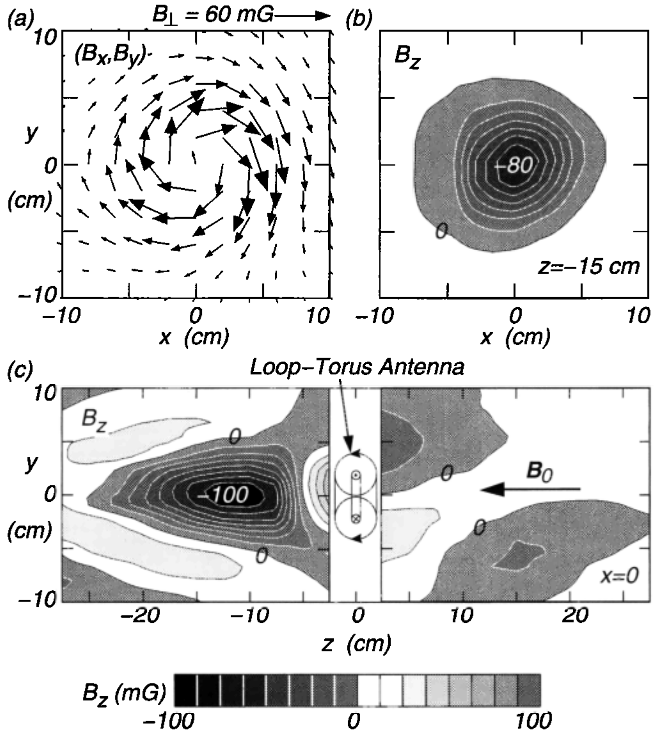


**Figure 9.** Snapshot of the magnetic field components excited by a current pulse to a loop-torus antenna of positive helicity: (a) transverse fields dominated by $B_\theta$ due to the torus, (b) axial field $B_z$ due to the linked loop, and (c) axial field $B_z$ in the central $y-z$ plane showing a large amplitude asymmetry along $\mathbf{B}_0$ associated with helicity conservation.

dipole in a streaming magnetoplasma. The results are relevant to observations of magnetic signatures near asteroids in the solar wind [*Kivelson et al.*, 1993]. Several recent theoretical and numerical investigations of whistler wings have supported the observations [*Baumgärtel et al.*, 1994; *Gurnett*, 1995; *Wang and Kivelson*, 1996; *Thomson et al.*, 1996].

## 6. Applications of Whistlers

Ever since the basic theory for whistlers was developed, the potential for remote diagnostics of the ionosphere has been obvious. The average electron density can be obtained from the dispersion of low-frequency whistlers or, more accurately, from "nose whistlers" [*Helliwell*, 1965]. Electron temperature, large-scale electric fields, ion composition, and fractional densities have been measured [*Russell et al.*, 1971; *Sazhin and Hayakawa*, 1992]. Magnetic fields in solar and laser plasmas have been estimated, and the presence of non-Maxwellian electron distributions can be inferred from whistler emissions.

Ground-based ionospheric modification experiments are pursued to generate ELF/VLF signals in a controlled way [*Rowland et al.*, 1996; *Barr and Stubbe*, 1997]. Since these signals can penetrate deep into Earth, they have important applications for communication with submarines [*Vego*, 1987] and subterranean imaging of mines and man-made structures [*Thiel et al.*, 1996]. Direct excitation of VLF signals from satellites have encountered setbacks [*Sonwalkar et al.*, 1994b; *Stone and Bonifazi*, 1998] but hold potential for many interesting applications [*Penzo and Ammann*, 1989].

The detection of seismogenic VLF emissions from space is an important activity which holds a potential for predicting earthquakes and volcanic eruptions [*Hayakawa et al.*, 1993; *Molchanov et al.*, 1993]. However, as with most new results, they are not without controversy [*Rodger et al.*, 1996].

There are many applications of whistler wave phenomena in laboratory plasmas. Helicon plasma sources are used in the fabrication of microelectronic devices such as large-scale integrated circuits used in every computer. Whistlers waves couple RF power efficiently into the electrons and produce dense uniform plasmas for high-quality plasma processing [*Mieno et al.*, 1992; *Ellingboe and Boswell*, 1996; *Chen*, 1996]. Whistlers are also useful to heat electrons and drive dc currents in toroidal fusion devices [*de Assis and Busnardo-Neto*, 1988].

Pulsed power technology produces short (20 ns), high-power ($10^{12}$ W) pulses to accelerate particle beams for inertial fusion [*Weber et al.*, 1995]. Inductively stored energy is transferred to a load via a plasma opening switch whose transient EMHD current propagates at the whistler speed. The electrons are magnetized by the wave magnetic field hence the current penetration is nonlinear [*Fruchtman*, 1991].

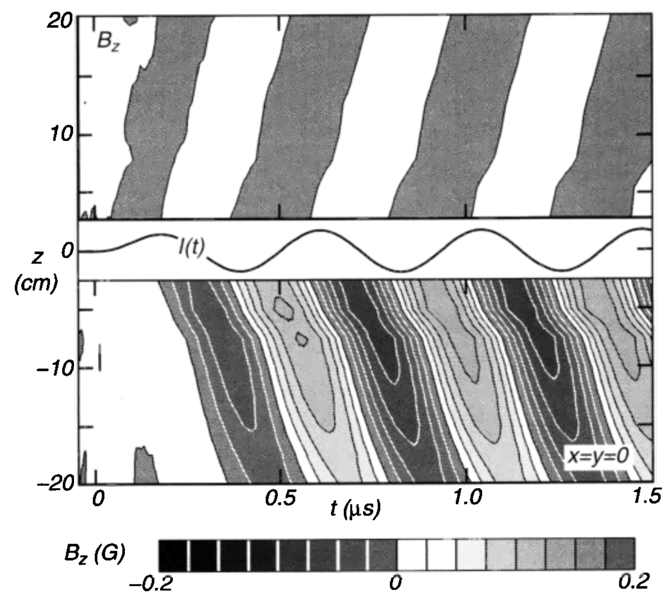


**Figure 10.** Axial field component, $B_z(z,t)$, excited by a positive-helicity loop-torus antenna located at $z = 0$ and driven by a sinusoidal current $I(t)$ (central trace). Because of helicity conservation, a predominantly positive-helicity whistler wave is excited along $\mathbf{B}_0 \parallel \mathbf{z}$.

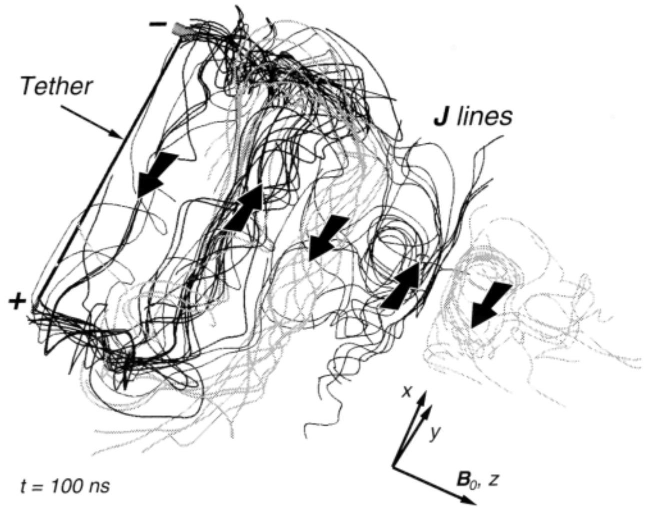


**Figure 11.** Snapshot of measured current density lines $\mathbf{J}(\mathbf{r})$ excited by tethered electrodes in a laboratory magnetoplasma. An applied current pulse ($\Delta t \simeq 70$ ns) generates helical plasma currents at each electrode, which are closed by electron Hall currents induced by the insulated tether wire. Multiple current loops are excited which propagate in the whistler mode along $\mathbf{B}_0$. A second current system (not shown here) propagates in the $-\mathbf{B}_0$ direction.

## 7. Forefront and Open Topics in Whistler Wave Research

Although whistler phenomena have been studied for 100 years, there are still many interesting questions left. Some problems are better suited for experiments in space; others are better suited for experiment in the laboratory. The low collisionality and large scale-length of space plasmas is ideal for observing wave-particle and wave-wave interactions. The former require time-resolved measurements of the electron distribution function combined with complete wave measurements; the latter require multipoint data for correlation and bispectral wave analyses. Such measurements could advance the knowledge of phase space instabilities, transport processes in velocity space, particle acceleration processes involving whistlers, and nonlinearly coupled modes.

Laboratory experiments are highly suited for performing multipoint measurements, excitation of large-amplitude waves, and controlled parameter variations. A basic linear problem which could be measured in a large laboratory plasma is the coupling of whistlers into the Earth-ionospheric waveguide. The properties of nonlinear whistlers whose wave amplitude exceeds the ambient field are just beginning to be studied. These waves can create magnetic null points, reverse the helicity density, and propagate at a speed which depends on amplitude and field direction.

The role of the whistler mode in magnetic reconnection and the dynamics of narrow current sheets is presently of great interest [*Biskamp et al.*, 1997; *Yamada et al.*, 1997]. Fundamental questions of helicity and energy transport during reconnection are also the focus of present research [*Canfield and Pevtsov*, 1998].

Novel methods of wave excitation with beams and antennas are successfully explored in the laboratory prior to possible applications in space [*Griskey et al.*, 1997; *Rousculp et al.*, 1997; *Kostrov et al.*, 1998a]. The mechanisms for electron acceleration in the near-zone of antennas could be resolved experimentally since it is of broad interest in various fields [*Karpman*, 1985; *Kolobov and Economou*, 1997; *Chen*, 1996].

The capability of measuring current systems in three-dimensional space and time opens up many useful investigations such as currents carried by pulsed beams [*Nakamura et al.*, 1989] or thermal currents generated by heat pulses, which, in EMHD, form flux ropes [*Stenzel and Urrutia*, 1996]. The high sensitivity of magnetic measurements allows one to study whistler thermal noise in 1 eV plasmas or to resolve temperature changes of $\Delta kT_e \simeq 10^{-3}$ eV for detailed heat transport studies.

Active experiments in space or ground-based wave injection experiments form a bridge between laboratory and observational space research. The applied signals can be controlled, the plasma parameters are set by nature, the effects are usually detected remotely, and for most experiments the plasma is unbounded although not uniform. Precipitation of energetic electrons by whistlers is an important topic of energy transfer from the magnetosphere to the atmosphere. Controlled precipitation by VLF injection may be of interest for communication and aeronomy. Active whistler wave injection experiments from space deserve more attention. Free-flying or tethered diagnostic packages are needed to measure spatial wave properties.

Basic research in laboratory and space plasmas have fundamentally the same scientific goals, i.e., to observe and understand new plasma phenomena. In the labora-

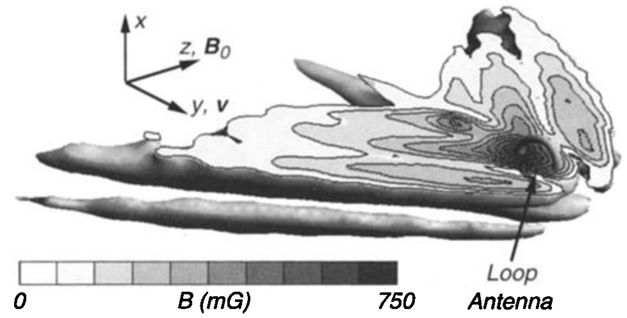


**Figure 12.** Whistler wings in the perturbed magnetic field of a current loop moving with velocity $\mathbf{v} \perp \mathbf{B}_0$. The wing is constructed by Huygens principle from a superposition of delayed whistler wavelets from displaced loop positions [*Urrutia et al.*, 1994b]. Similar structures have been observed behind magnetized asteroids in the solar wind [*Kivelson et al.*, 1993].

tory the goal is to isolate a physical process and study it in detail under controlled conditions. In space this is usually not possible, and one has to understand a complex coupled system from a limited set of passive observations. While the approaches, methods, and applications often vary, each activity can only benefit from learning about the different aspects of whistler wave research.

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