Paper 3: Some background on whistler waves

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1 Background

Whistler waves are dispersive electromagnetic waves carried by the electrons in a magnetized plasma. They are right-handed waves that propagate between the ion and electron cyclotron frequencies. They propagate along the background magnetic field within a cone given by $cos\theta = \omega/\omega_{ce}$, so for $\omega \ll \omega_{ce}$, they can propagate at almost any angle with respect to $\mathbf{B_0}$. A simple way to write the dispersion relation in the limit of $\omega \ll \omega_{ce}$ is:

$$\omega = \omega_{ce}\left(\frac{ck}{\omega_{pe}}\right)^2.$$

The key point is that for whistlers, the frequency is non-linear with the wavenumber, so the group velocity $\partial\omega/\partial k$ depends on k (and therefore also on ω):

$$v_g = 2c\frac{\sqrt{\omega\omega_{ce}}}{\omega_{pe}}$$

(see Figure 1). Because of this, higher frequencies propagate faster than lower frequencies so whistlers were originally detected a century ago due to their characteristic falling whistle tone (see Figure 2).

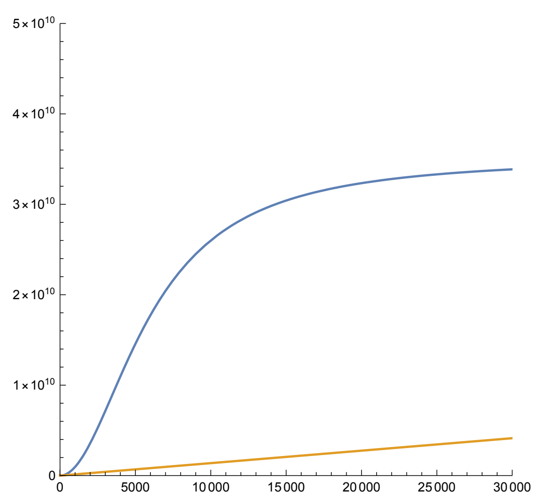

Figure 1: Whistler dispersion relation. The wave doesn't propagate above the electron cyclotron frequency. Phase velocity always exceeds the Alfvén speed. Below the ion cyclotron frequency, the whistler wave becomes the Alfvén wave (lower left corner).

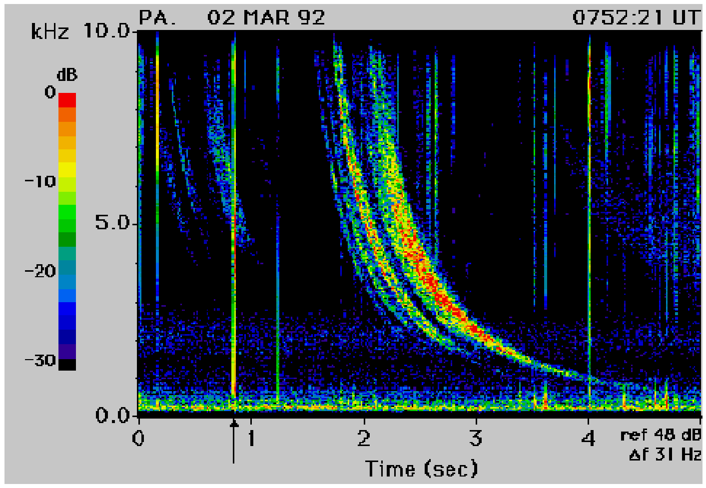

Figure 2: Whistler observation. Plot of the characteristic falling tone of a whistler wave recorded at Palmer Station, Antarctica. If played into a speaker, this would sound like a descending tone for about 2 seconds.

Laboratory studies of whistler waves were pioneered by R. L. Stenzel at UCLA. In over 50 papers, the Stenzel team carefully mapped out dispersion relations, phase, and group velocites [Stenzel 1976, Stenzel 1999]. Coherent whistler waves and bursts were excitated by either magnetic coils [Stenzel 1993, Rousculp 1995], or electrodes [Urrutia 1989, Urrutia 1994]. The Stenzel device (a precursor to the LAPD device) used a large BaO cathode (0.5 m) to produce a magnetized ($0 < B_0 < 150\ G$), cold ($T_e \leq 2\ eV$, $T_i \leq 0.2\ eV$), low density $n_e = \leq 10^{12}\ cm^{-3}$ plasma.

When a short burst of current is applied to a coil antenna, a detached structure is formed that propagates away from the antenna at the whistler group velocity [Stenzel 1990, Stenzel 1999]. In some cases, the structure is a nearly spherical vortex. It can be demonstrated that the current density in these structures is parallel to the wave magnetic field ($\mathbf{J} \propto \mathbf{B_{wave}}$) so the structures can be thought of as force free in the context of electron MHD (EMHD). A simple loop antenna launches whistler packets in both directions, with opposite EMHD helicity.

In a sequence of over a dozen papers beginning with [Urrutia 1989, Stenzel 1993], the Stenzel group began to study pulsed currents carried by whistler structures. In these experiments, the background magnetic field was very low ($B_0 \leq 20\ G$) so ions were unmagnetized, and experiments were performed in the afterglow, so that cathode currents were not present. The full three-dimensional magnetic field $\mathbf{B}(\mathbf{r}, \mathbf{t})$ was mapped point-by-point from $> 10^5$ highly repeatable shots, so that the current density could be calculated directly by Ampere's law: $\mu_0 \mathbf{J}(\mathbf{r}, \mathbf{t}) = \nabla \times \mathbf{B}(\mathbf{r}, \mathbf{t})$. Measurements showed that indeed contours of components of $\mathbf{B}$ and $\mathbf{J}$ had very similar topologies.

When high currents are applied to the antennae, non-linear effects are observed [Urrutia 1991, Urrutia 1996]. In some cases, wave fields can exceed the background field $\mathbf{B_0}$ [Stenzel 2006], and the field energy density far exceeds the particle thermal energy ($\tilde{B}^2/2\mu_0 \cong 10^4 nkT$) [Urrutia 1991]. The physics idea is that the intense electromagnetic pulse from the antenna rapidly heats the electrons. The high conductivity channel produced by the hot electrons allows the nonlinear wave to penetrate anomalously into the collisional background plasma [Urrutia 1991]. We believe that this mechanism could be at play in SSX.

2 References

References

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