# MANIFESTATIONS OF LOWER HYBRID RESONANCE IN NONDUCTED WHISTLER WAVE PROPAGATION IN THE MAGNETOSPHERE

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## 1. Introduction

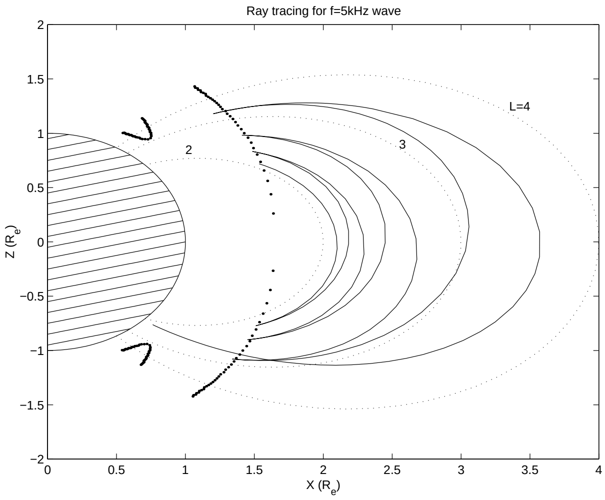
The importance of lower hybrid resonance (LHR) effects for understanding of whistler wave propagation in the magnetosphere has first been established by Kimura (1966). He has shown that a whistler mode wave can be reflected from the magnetospheric (or upper ionospheric) region where the LHR frequency of the medium exceeds the wave frequency. As a consequence, the wave can be trapped inside the region with a minimum in LHR frequency profile, in particular, on the closed field lines in the magnetosphere, or in some special regions in the upper ionosphere where a minimum of LHR frequency profile may be formed due to specific behaviour of the ion effective mass. New observations of nonducted VLF waves aboard the MAGION 4 and 5 satellites stimulated interest to further studies of various phenomena connected with nonducted whistler propagation in which LHR effects are of principal importance, in particular lower hybrid resonance (LHR) noise bands; LHR whistlers and LHR spherics; and magnetospherically reflected (MR) whistlers. In the present report, we review some results of the investigations of LHR associated phenomena.

## 2. Main features of nonducted whistler wave propagation in a smooth magnetosphere

In the framework of geometrical optics, the propagation of whistler mode waves is determined by the dispersion relation:

$$\omega^2 = \omega_{\rm LH}^2 \frac{k^2}{k^2+q^2} + \omega_H^2 \frac{k_\|^2 k^2}{(k^2+q^2)^2} \equiv \frac{\omega_{\rm LH}^2}{1+q^2/k^2} + \frac{\omega_H^2 \cos^2\theta}{(1+q^2/k^2)^2} \,. \quad (1)$$

Here $\omega_{\rm LH}$ is the lower hybrid resonance frequency, $k^2 = k_\|^2 + k_\perp^2$ where $k_\|$ and $k_\perp$ are components of the wave normal vector parallel and perpendicular to the ambient magnetic field, $q^2 = \omega_p^2/c^2$, $\omega_p$ and $\omega_H$ are electron plasma frequency and gyrofrequency, respectively, and $\theta = \cos^{-1}(k_\|/k)$. Whistler mode waves described by the dispersion relation (1) have different character depending on the paramter $k^2/q^2$. For $k^2/q^2 \lesssim 1$, which corresponds to quasi-longitudinal mode of propagation, the wave magnetic field dominates over the wave electric field; at the same time, the wave group velocity is of the order of $\omega/k \sim c\omega_H/\omega_p$. For $k^2/q^2 \gg 1$, the wave becomes quasi-electrostatic, and its group velocity essentially decreases. The corresponding regime of propagation is often referred to as quasi-resonance one. In general, whistler-mode waves exist at $\omega > \omega_{\rm LH}$ as well as $\omega < \omega_{\rm LH}$, however, the last range is accessible only for waves in quasi-longitudinal mode of propagation. As for quasi-resonance waves having $k^2 \gg q^2$ and the wave normal angles $\theta$ close to $\pi/2$, they do not propagate in the regions where $\omega$ is significantly smaller than $\omega_{\rm LH}$. It is instructive to consider a typical whistler mode wave trajectory in the magnetosphere, and the variation of important wave parameters along the ray path. Figure 1 shows the ray trajectory for 5-kHz wave launched vertically from 500 km altitude at a latitude of $\lambda = 45^o$, and Figure 2 provides a summary of the propagation features for this wave. We see that after the first few magnetospheric reflections, the wave normal angle $\theta$ becomes very close to $\pi/2$, the parameter $k^2/q^2$ becomes very large, so that the wave is quasi-electrostatic. At the same time, the transversal group velocity $v_{g\perp}$ becomes very small in comparison with typical $v_{g\|}$ (which is violated only in the vicinity of the "reflection" point where $v_{g\|} = 0$), so that the wave moves predominantly along the field line.



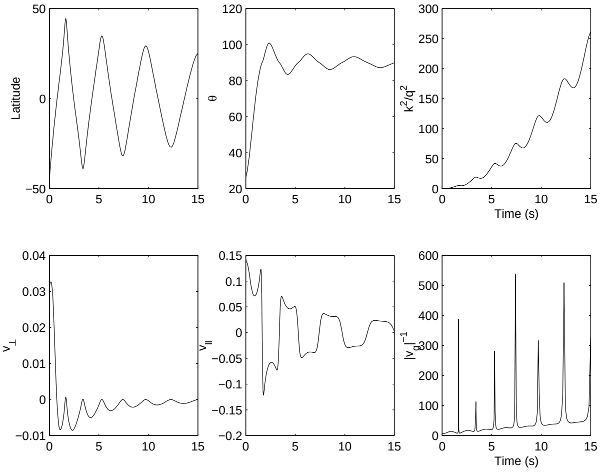
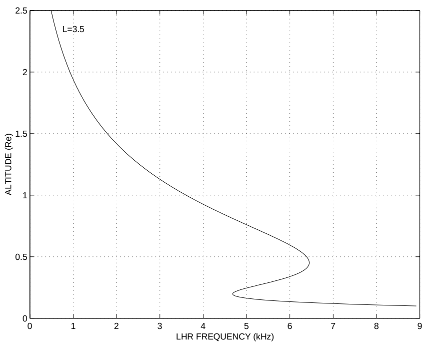




Figure 1. Figure 2.

3. Quasi-electrostatic whistler mode wave trapping in LHR waveguide

Although the wave propagation inside the waveguide was considered in many papers beginning from the pioneering work by Smith et al. (1966), the mechanism of the waveguide feeding remained unclear. Typical LHR frequency profile in the outer ionosphere is shown in Figure 3. In the plane ($\omega_{\rm LH}$, ALTITUDE), the wave trajectory corresponds to a vertical line $\omega = $ const. If a quasi-electrostatic wave moves towards increasing values of $\omega_{\rm LH}$, its group velocity decreases, and the wave is reflected in the vicinity of the point where this line crosses the LHR frequency profile. Thus, waves with the frequencies $(\omega_{\rm LH})_{\rm min} < \omega < *(\omega_{\rm LH})_{\rm max}$, if exist in the waveguide (that is below $h_{\rm max}$), would be trapped inside the waveguide. But, at first sight, the waveguide could not be fed either from above, or from below.



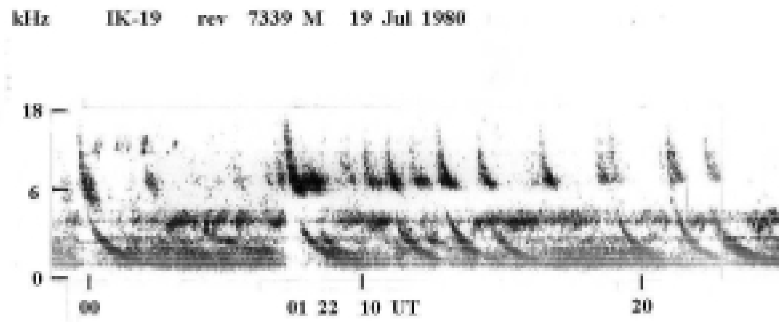




Figure 3. Figure 4.

A mechanism of LHR waveguide feeding by quasi-electrostatic whistler mode waves has been explored by Jiříček and Shklyar (1999). The key point in this mechanism is a two-dimensional character of the wave propagation. It results in that the wave longitudinal motion takes place in a time dependent potential. As was shown above (see Figure 2), when one-hop or multiple-hop nonducted whistler wave crosses LHR maximum in the outer ionosphere, it moves towards lower $L$-shells. The trapping of downwards propagating quasi-resonance waves into LHR waveguide takes place if the wave frequency is close to the local maximum of LHR frequency, and the values of maximal LHR frequency along geomagnetic field lines increase with decreasing $L$-shells.

Closely related to the wave trapping is the problem of formation of LHR whistler traces (Bošková et al., 1988). An example of the corresponding spectrogram is shown in Figure 4. Such a spectrogram should be expected when a satellite is below the local maximum of LHR frequency (see Figure 3). In this case, the lower cutoff and anomalously large group time delay correspond not to the local, but to the maximal LHR frequency along the filed line.

4. LHR noise as a signature of magnetospheric whistler reflections

The noise band at the lower hybrid resonance known as LHR noise (or LHR hiss) has been detected in the VLF recordings in the plasmaspheric regions of magnetosphere beginning from the observations of the Alouette satellite. Few references below could serve as milestones in the history of investigations of this phenomena (Barrington et al., 1963; Brice and Smith, 1965; Burtis, 1973). Basing on the papers listed above, important features of LHR noise can be summarized as follows: sharp lower frequency cutoff that in general varies with varying satellite position; connection with nonducted whistlers and magnetospheric reflections; and predominant observation with electric antennas. An example of MAGION 5 VLF spectrogram detected with electric and magnetic antennas are shown in the left and right panels of Figure 5, respectively. While usual whistlers are seen in both panels, LHR noise is registered only by the electric antenna. This illustrates the well known fact that LHR noise represents a type of quasi-electrostatic waves.

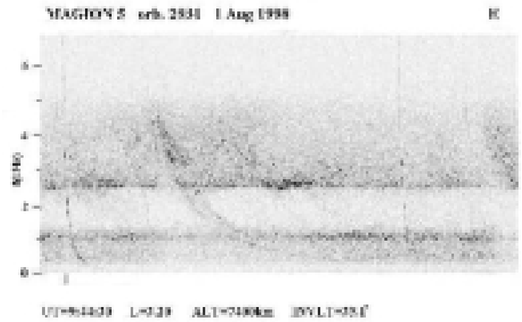


Figure 5a.

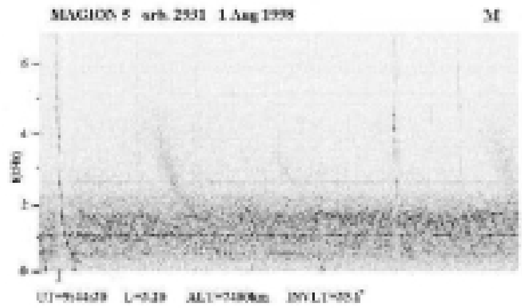


Figure 5b.

Although the problem of LHR noise cannot be completely reduced to geometrical optics, and linear and nonlinear wave conversion should play a part, it is first of all necessary to explore the consequences of the consideration in the frame of geometrical optics. If not to assume that LHR noise is excited as the result of some wave conversion (or wave generation) process, then it should represent a kind of waves which are always present in the magnetosphere. Obviously, the first candidates are the whistler mode waves excited by lightnings which, being trapped due to the magnetospheric reflection, fill up the magnetosphere. As was mentioned above, whistler mode waves may propagate at frequencies $\omega > \omega_{\mathrm{LH}}$ as well as at $\omega < \omega_{\mathrm{LH}}$. Why then the spectrum usually observed in the experiment has a pronounced maximum at $\omega = \omega_{\mathrm{LH}}$? To explain this, we recall that in the course of magnetospheric propagation in a smooth plasmasphere, a whistler mode wave naturally turns into quasi-electrostatic regime, with a significant decrease of the wave group velocity. From the energy conservation which requires the energy flux to be constant along the ray path one can easily understand that the region of minimum group velocity should correspond to maximum wave amplitude. It appears that the minimum group velocity of the wave is achieved in the region where the wave frequency is very close to the local LHR frequency. To examine how pronounced this effect is, we turn to the lower panel of Figure 2 which shows very sharp maxima of the quantity $|v_g|^{-1}$ at the reflection points. Since $v_{g\perp}$ is very small, the minimum $|v_g|$ is achieved in a close vicinity of the point where $v_{g\|} = 0$. As follows from (1), it takes place at $\omega = \omega_{\mathrm{LH}}[k^2/(k^2+q^2)]^{1/2}$ which for typical values of the parameter $k^2/q^2$ at the reflection point is very close to $\omega_{\mathrm{LH}}$. Thus, wherever the satellite is, it should register a pronounced maximum of the electrostatic spectral intensity at the local LHR frequency. Figure 6 shows an example of LHR noise registration along MAGION 5 orbit.

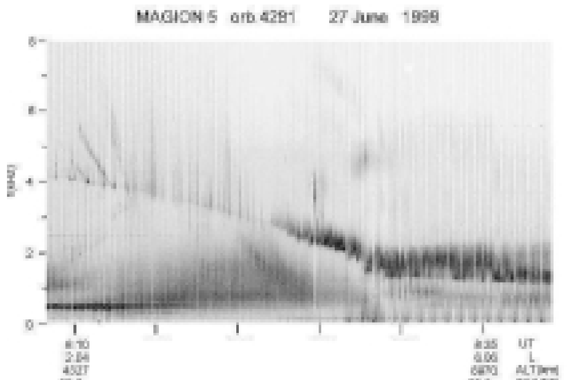


**Figure 6.**

5. MR whistlers

Of the many phenomena associated with the nonducted propagation of whistler waves, magnetospherically reflected (MR) whistlers are among the most interesting. The key point in understanding of the formation of MR whistler traces is the idea (Kimura, 1966) of LHR wave reflection in the magnetosphere. This understanding has been achieved in basic studies of MR whistlers by Smith and Angerami (1968) and Edgar (1976). The ideas of these authors have been used by Shklyar and Jiříček (2000) for numerical simulation of various types of MR whistler spectrograms observed by MAGION 4 and 5. Analysis of complex spectrograms found in experimental data shows that their peculiar pattern is connected with specific illuminating region and depends essentially on the observation point and geomagnetic activity. Large amount of experimental data available from MAGION 4 and 5 measurements provide evidences that the existence of extended plasmasphere is a necessary condition for the formation of MR whistler spectrograms. In the investigation of MR whistlers, we proceed from general features of nonducted wave propagation in the plasmashere, and turn from the analysis of ray trajectories into simulations of the whole spectrograms. This yields understanding of several features of MR whistler spectrograms, such as principal dependence of a spectrogram on the observation point rather than on the illuminating region; the correspondence of the nose frequency to the wave packet propagating along the geomagnetic field ($v_{g\perp} = 0$); the decrease of the nose frequency with increasing trace number, and others (see Shklyar and Jiříček, 2000 for details). Examples of rather complicated spectrograms, real and simulated, are shown in Figure 7 and Figure 8, respectively.

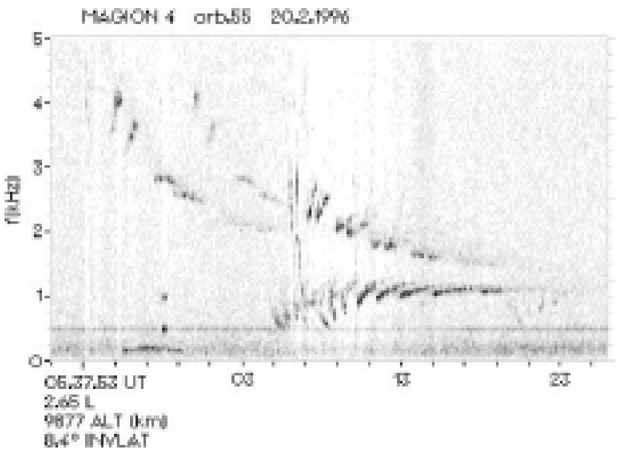



Figure 7.

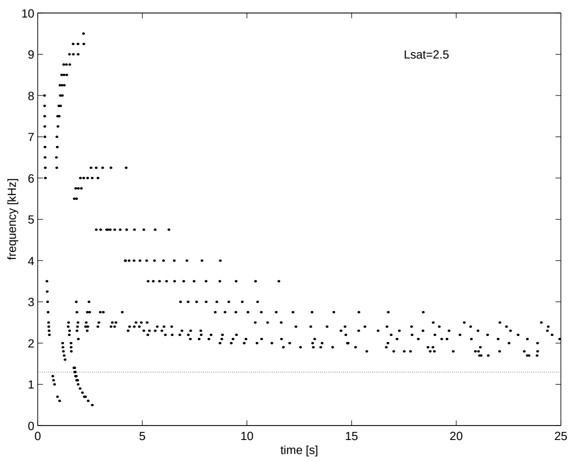



Figure 8.

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