Linear mode conversion between cold plasma waves mediated by a density inhomogeneity in the ionosphere

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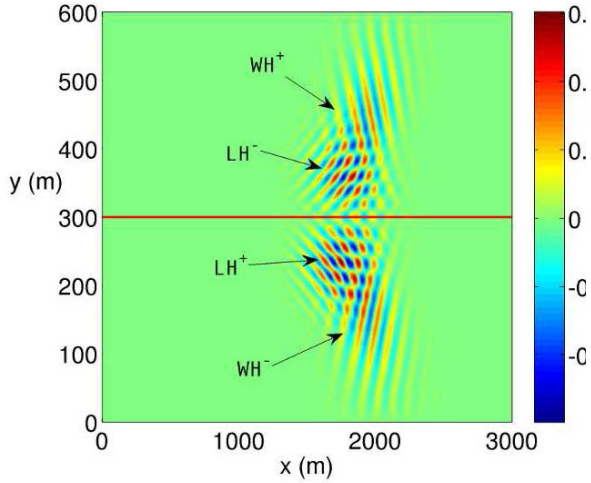
An enhancement of wave activity has been often observed by rockets and satellites in the presence of density depletions (striations) in the upper ionosphere. When a wave packet composed of short wavelength modes travelling in an homogeneous plasma region encounters such an inhomogeneity, it can resonantly excite long wavelength waves via a linear mechanism known as mode conversion. We address here the process of linear mode conversion between lower hybrid and whistler waves, mediated by a density striation, using a scalar-field formalism (in the limit of cold plasma linear theory) which we solve numerically. We show that the mode conversion can effectively transfer a large amount of energy from the short to the long wavelength modes, and we present a general criterion for the width of the striation that, if fulfilled, maximizes the conversion efficiency [1]. This process is interesting in a space weather perspective because whistler waves can affect the lifetime of energetic electrons trapped in the geomagnetic field.

Whistler and lower hybrid waves are frequently observed in all regions of the Earth's magnetosphere. They belong to the same branch of the dispersion relation for waves in a magnetized plasma. Whistler modes are electromagnetic waves with frequency between the ion and electron cyclotron frequencies, whereas lower hybrid waves are predominantly electrostatic and their frequency approaches the lower hybrid frequency in the limit of infinite wavevector for exactly perpendicular propagation. The close relationship between these two wave modes suggests that linear mode conversion can likely occur wherever inhomogeneities are present. In the ionosphere, enhancement of lower hybrid/whistler wave activity has been often associated with density depletions, so-called lower hybrid cavities (LHCs) or lower hybrid solitary wave structures (LHSS). Both sounding rockets [2-5] and satellites [6-7] have observed intense, primarily electrostatic waves in the presence of density cavities. The depth of the density depletions measured in the rocket experiments were as large as 80%, although measurements by the Freja satellite suggested that the depletions were much shallower, typically a few per cent. Lower hybrid cavities were also observed by the Viking and Cluster satellites at much higher altitudes [8], with depletions ranging from a few to 30% of the background density. A statistical survey of Freja measurements [9] has shown that in a vast majority of cases the density depletion is well fitted by a Gaussian shape and the average cavity width is on the order of 30 meters, corresponding to few ion gyroradii. Theoretical studies showed how lower hybrid waves could be trapped inside such structures.



Conversion of a lower hybrid wave packet (LH^+) into two whistler packets (WH) and a reflecting lower hybrid (LH^-) upon impinging on a density striation (red line)

In addition, nonlinear theory indicates that the cavities could collapse due to the ponderomotive force of the lower hybrid waves trapped inside . While a complete theory that would explain the formation of the cavities and the propagation of waves inside them is still missing, some observations showing circularly polarized low

frequency waves support the idea that the density gradients are pre-formed and that whistler waves impinging on a density cavity or gradient can mode convert to lower hybrid waves. This process was originally studied by Bell and Ngo [10] to explain observations of electrostatic waves excited by whistlers throughout the ionosphere and magnetosphere, and this work was recently augmented in [11]. Formal solutions of the wave equations in a cold magnetized plasma showed that the process involves a transmitted and reflected whistler wave and two lower hybrid waves. In addition, linear mode conversion implies that the inverse process is also possible: an incident LH wave can mode convert to a whistler mode. Borisov [12] proposed this mechanism in ionospheric modification experiments to explain the conversion of lower hybrid waves that are produced by the decay of HF radio waves to whistler waves on density irregularities. He estimated a very small conversion efficiency ($\approx 10^{-6}$) for typical experimental parameters. In addition to observations, several laboratory experiments have addressed the physics of linear mode conversion, mimicking the conditions found in the magnetosphere. Experiments at the Large Plasma Device (LAPD) at UCLA have investigated the conversion of whistler to lower hybrid waves [13], and of lower hybrid to whistler modes [14] in a cylindrical field-aligned density depletion. None of these works, however, have focused on the conversion efficiency, which is the primary goal of this paper. Recently, Eliasson and Papadopoulos [15] have presented a numerical study of the mode conversion between lower hybrid and whistler waves on one or more density striations. Their theory is valid in the cold plasma limit and for shallow striations, and they have presented an empirical criterion for the width of the striation that , if satisfied, would maximize the efficiency of the conversion. The same formalism and numerical method has been used to study the problem of whistler wave attenuation on density striations (the so-called ’20dB puzzle’) by Shao et al.[16].

In this paper, we address the problem of linear mode conversion between lower hybrid and whistler modes on a density striation from a theoretical standpoint . The problem is set up as the following. A wave-packet composed of quasi-perpendicular lower hybrid modes is initialized in a region of uniform magnetized plasma. The packet propagates according to its group velocity until it encounters a depletion in the density, in the direction perpendicular to the background magnetic field. The effect of the density striation is to couple linear modes that would otherwise be uncoupled in the absence of any inhomogeneities. This is a completely linear mechanism, that does not need any non-linear effect. Hence, a fraction of the energy of the lower hybrid packet is transferred to whistler waves. The scope of the present paper is to analyze what is the efficiency of such energy transfer, what are the variables that affect such efficiency, and under which conditions the efficiency is maximum

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