Journal of Atmospheric and Solar-Terrestrial Physics 142 (2016) 35–42

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The role of deviation of magnetic field direction on the beaming angle: Extending of beaming angle theory

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ARTICLE INFO

Article history:
Received 16 February 2015
Received in revised form
19 January 2016
Accepted 26 February 2016
Available online 2 March 2016

Keywords:
Beaming angle
Jones' formula
Magnetic field direction
Density gradient

ABSTRACT

In the beaming angle theory, the magnetic field direction is assumed perpendicular to the normal boundary, and the prediction of this theory, from beaming angle is base on the Jones' formula. We investigate the effect of deviation the magnetic field direction respect to normal boundary direction. In this study, we present new conditions that under these conditions two modes, extraordinary and ordinary modes waves can match. Also, we show for these cases the beaming angle does not correspond to Jones' formula. This effect leads to the angles larger and smaller than the angle estimated by Jones' formula. This effect on the mode conversion process becomes important in a case where local fluctuations in the direction of the density gradient vector or the magnetic field direction are observed. By comparing the beaming angle from observations with the beaming angles resulting from different $\Delta\Phi$, we showed a $\Delta\Phi$ about 3 to 5° are necessary in consistence with observation.

1. Introduction

Jones (1982, 1981, 1986), Jones et al. (1987) applied the LMCW (linear mode conversion "window") theory to explain the generation process of nonthermal continuum radiation (Jones and Leblanc, 1987). The term "window" for radio waves in a stratified magneto plasma is used to denote the phenomenon whereby waves in one magneto-ionic mode can penetrate through a region where, according to a simple ray theory, they would be evanescent, and can energy on the far side in a different magneto-ionic mode (Ellis, 1956; Budden, 1980, 1985).

Budden (1980) has reviewed the theory of radio windows and presented a formula for the window attenuation in dB for the Z–O window. For the center of window, two Z and O –mode waves can match together, but for both side of center, there is a barrier which attenuates the wave, but some of energy can tunnel through the evanescence layer between Z- to O mode branches (Budden, 1980; Weitzner and Batchelor, 1973; Kalaee and Katoh, 2014). The radiation passing through the centre of the window which suffers no attenuation is beamed away latitudinally from the magnetic equatorial plane at the angle (Jones, 1988);

$$\beta_{LMCT}=\tan^{-1}\left(\frac{\omega_c}{\omega_p}\right)^{1/2}, \tag{1}$$

where ω_c, ω_p and β_{LMCT} represent the electron cyclotron frequency, the electron plasma frequency and the beaming angle from LMCT prediction, respectively. The frequency of waves emitted from the radio window is determined by the local plasma frequency at the site of mode conversion. The Jones relation (Eq. 1) only works if the magnetic field direction is perpendicular to the normal boundary. In general, we define β as the beaming angle with respect to the magnetic equatorial plane.

Previous studies showed the mode conversion with a maximum efficiency takes place where two branches of Z-mode ($\omega_p < \omega < \omega_{UHR}$; so called the UHR-mode, where ω_{UHR} represent the upper hybrid resonance frequency), and LO-mode (ordinary) waves are matched (Budden, 1980; Budden and Jones, 1987; Jones, 1981, 1986, Jones et al., 1987; Kalaee et al., 2009, 2010).

Kalaee et al. (2009) investigated a linear mode conversion process among UHR-mode, Z-mode, and LO-mode waves by a computer simulation. They studied the dependence of the conversion efficiency on the wave normal angle of the incident wave, the frequency of the incident wave, and the plasma frequency. The characteristics of the wave coupling process occurring in the cold magnetized plasma were examined in detail for the case of an inhomogeneity of plasma density lying perpendicular to the ambient magnetic field. They showed that the highest conversion efficiency was obtained under the specific condition of the wave normal angle for the incident waves (We will present a detail of

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http://dx.doi.org/10.1016/j.jastp.2016.02.021
1364-6826/

this condition in Section 2). In the specific case of such critical wave normal angles, the simulation results indicated that the wave normal angle of LO-mode waves is nearly parallel to magnetic field at the site of mode conversion, which is consistent with previously reported results, such as those of Jones (1976), Jones et al., 1987 and Lembege and Jones (1982).

They also showed that the range of the critical normal angle varied depending on both the plasma frequency and the wave frequency. The simulation results also revealed that, when the steepness of the density gradient was taken into consideration, efficient mode conversion could be expected even in the case of the mismatch of the refractive indexes preventing the close coupling of plasma waves. Schleyer et al. (2013, 2014) studied the linear mode (LMC) conversion of Langmuir/z –mode waves to electromagnetic radiation. They calculated the energy and power conversion efficiencies in a warm, magnetized plasma as functions of incidence angle, temperature, and orientation of the density gradient relative to magnetic field. The results showed the both efficiencies depend strongly on the angle between the ambient density gradient and the ambient magnetic field. The efficiencies are shown to be maximum for approximately perpendicular density gradients and minimal for parallel orientation.

Also, a numerical study of mode conversion in warm, magnetized plasmas with various magnetic field strength was presented by Kim et al. (2013). They showed for weakly magnetized plasmas, the radiations produced over a wide range (0–90°) of the angle between the ambient density gradient and the ambient magnetic field and for intermediately magnetized plasmas, they are produced most strongly in the range (40–60°).

On the other hand, Hashimoto et al. (2006) reported an example of CRRES observations reveals a possibility that kilometric continuum has been radiated as wide beam emissions, contrary to the linear mode conversion theory. Also, the simultaneous observations of kilometric continuum by IMAGE and GEOTAIL have indicated another new evidence of a very broad emission (Hashimoto et al., 2006; Boardsen et al., 2008). Also, wide band emissions of nonthermal continuum observed by CLUSTER. They have also been observed at lower frequencies (Grimald et al. 2008; Grimald and Santolík, 2010; Décréau et al., 2015). Décréau et al. (2015) have presented morphological properties of beams radiated during NTC wave events characterized by wide banded harmonic signatures. Also, satellite observations show some local fluctuation in the density gradient in the equatorial plasmasphere that leads to a variation of the angle between the local magnetic field and density gradient, which has not been studied in detail for the radio window theory. Darrouzet et al. (2006) and De Keyser et al. (2007) analyzed a plasmasphere pass by CLUSTER to study the overall geometry of the plasmaspheric density structure, using gradient computation techniques. Darrouzet et al. (2006) analyzed the plasmasphere pass on 7 August 2003, at 14:00 LT and between −30° and +30° of magnetic latitude MLAT. Fig. 1 illustrates the angle between the magnetic field vector B and the density gradient ∇ne.

In the present paper, we investigate the effect of deviation the magnetic field direction respect to normal boundary direction up to $\frac{\pi}{2} \pm \Delta\Phi$ ($\approx \pm 10^\circ$); since, our intention has been consideration of radiation near to equatorial plasmasphere, so, for this purpose, we have focused on this range, but in generally, there is no limitation. The situation of the magnetic field vector respect to normal boundary is schematically illustrated in Fig. 2.

By using Cluster data, Grimald et al. (2007) have been shown for a common source the beaming angle does not correspond to Jones' formula. In this study, we present new conditions that under these conditions two modes, Z- (extraordinary) and LO-(ordinary) modes can match. Also, we show for these cases the beaming angle does not correspond to Jones' formula. This effect leads to the angles larger and smaller than the angle estimated by Jones' formula. We discuss the conversion process by cold plasma theory. Finally, by adopting observed values of the beaming angle as a function of frequency from Hashimoto's report (2006), and by comparing the computing beaming angle from different $\Delta\Phi$, we estimated a $\Delta\Phi$ that it is necessary the beaming angle to have agreement with observation.

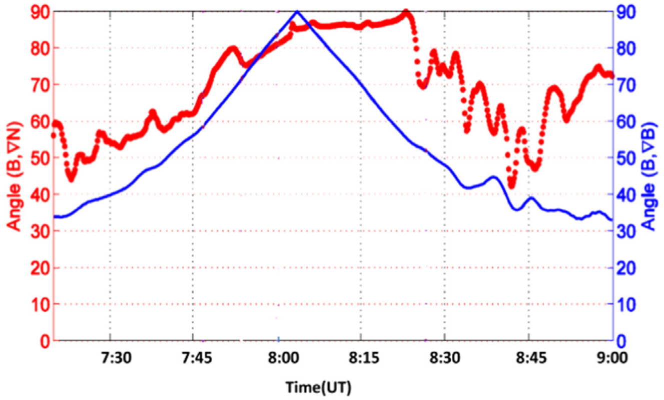

Fig. 1. The angles of ∇N and ∇B with respect to the local magnetic field B (red-dot and blue-solid curves, respectively), (Darrouzet et al., 2006). (For interpretation of the references to color in this figure legend,the reader is referred to the web version of this article.)

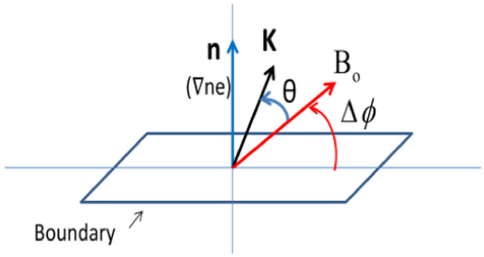

Fig. 2. The situation of the magnetic field vector respect to normal boundary.

2. The coupling properties of two mode waves based on the cold plasma theory

2.1. Case1: The magnetic field direction is parallel to the boundary, ($\Delta\Phi = 0^\circ$)

Here we review and discuss the coupling properties of extraordinary (Z-mode) and ordinary (LO) mode waves based on the cold plasma theory. By considering the dispersion relation for waves in a cold plasma, we obtain

$$n^2 = n_\parallel^2 + n_\perp^2 = 1 - \frac{2X(X-1)}{2(X-1) - Y^2\sin^2\theta \pm \Gamma}, \tag{2}$$

where n is the refractive index, $n_\parallel$ and $n_\perp$ are the parallel and perpendicular components of the refractive index, respectively,

$$\Gamma = \left[Y^4\sin^4\theta + 4(X-1)^2Y^2\cos^2\theta\right]^{1/2}, \tag{3}$$

$X = \left(\frac{\omega_p}{\omega_c}\right)^2$, $Y = \frac{\omega_c}{\omega}$, θ is the angle between the wave vector (k) and the external magnetic field (B_0), and the $+(-)$ sign gives the refractive index of the Z- (LO-) mode.

It is also clear from Eq. (2) that the two modes coalesce when the quantity Γ vanishes. This in turn requires that the conditions of $X = 1$and $\theta = 0^\circ$ should be simultaneously satisfied. The condition of $\theta = 0^\circ$, namely that $n_{\perp,LO} = n_{\perp,Z} = 0$, where $n_{\perp,LO}$ and $n_{\perp,Z}$ are