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Oblique electromagnetic electron cyclotron waves for Kappa distribution with AC field in planetary magnetospheres

R.S. Pandey, Rajbir Kaur *

Department of Applied Physics, Amity Institute of Applied Sciences, Amity University, Noida Sector-125, India

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Abstract

The dispersion relation for obliquely propagating relativistic electromagnetic electron cyclotron (EMEC) waves in collision-less magnetoplasma is obtained. Investigations for EMEC waves in magnetosphere of Jupiter, Saturn and Uranus have been done, in presence of perpendicular AC electric field for Kappa distribution function. The relativistic temporal growth rate is calculated using method of characteristic solution. Using the data provided by spacecrafts like Cassini, Voyager 1 and 2, while exploring the magnetosphere of Jupiter, Saturn and Uranus, is used to plot graphs showing growth rate being effected by various parameters. Comprehensive parametric analysis have been done at different radial distances of the planets. It is concluded that beside huge difference in magnetospheric configuration, temperature anisotropy remains the main source of energy in case of Jupiter and Uranus. While studying EMEC waves in magnetosphere of Saturn, it is inferred that growth rate attains maximum magnitude when angle of propagation increases. Also, the results and its interpretations explain how the growth of EMEC wave modifies in different magnetospheric conditions.

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1. Introduction

Low frequency plasma waves play a significant role in particle acceleration and plasma heating. They also play a dominant role in magnetospheric plasma by transferring momentum and energy among various populations of particle species. This paper summarizes theoretically the behavior of one the most important branch of such plasma waves in planetary magnetospheres, namely electromagnetic electron cyclotron (EMEC) harmonic waves. EMEC waves, in the frequency range of electron cyclotron frequency, have been observed in space (Kennel and Scarf, 1968; Wu and Davidson, 1972) and in surroundings of the outer planets (Barbosa and Kurth, 1980; Gurnett et al., 1986; Barbosa et al., 1990; Gurnett et al., 2005; Kurth and Gurnett, 1991). The particles whose Doppler shifted wave frequency lie in the neighborhood of gyrofrequency, interact strongly with these right-hand circularly polarized EMEC waves (Scharer and Trivelpiece, 1967). Such cyclotron wave-particle interactions provide a pathway through which waves can scatter, accelerate or thermalize the space plasma (Kennel and Petschek, 1966; Summers et al., 2007). The resonant wave-particle interactions supervise the established dynamics in space plasma and anisotropic electrons excite space plasma instabilities (Xiao, 2006; Lu and Wang, 2006), one of them being electron cyclotron waves. These wave-particle interactions are the major source of energy diffusion and pitch angle diffusion in planetary magnetosphere. Due to pitch angle diffusion, the diffused auroras are produced, which are observed

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* Corresponding author.
E-mail addresses: rspandey@amity.edu (R.S. Pandey), rkaur2@amity.edu (R. Kaur).

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by spacecraft, thus providing us the information of plasma oscillations in the magnetospheric environment.

In order to study dynamical behavior of planetary magnetospheres, it is important to pay attention to the role of electric field generated due to solar wind or rotation of planet along its spin axis. The significance of electric field in magnetospheric phenomena has been discussed by many researchers (Axford, 1969; Kivelson, 1976; Volland, 1973). Whistler mode instability triggered by time varying AC electric field has been studied in magnetosphere (Misra and Pandey, 1995; Pandey et al., 2003). The study of cyclotron waves in presence of perpendicular and parallel electric fields helps in explaining the different parts of electromagnetic spectrum. Parallel electric field contributes to parallel resonance velocity, giving maximum emission possibilities afterwards. Perpendicular electric field, modifies perpendicular velocity and contributes to energy exchange, leading to significant emissions of VLF signals therefore explaining the low frequency side of the spectrum (Misra and Pandey, 1995; Pandey et al., 2014; Pandey and Kaur, 2014). The importance of magnetospheric electric field can be realized by doing the extensive literature survey. Some of the highlighting conclusions were drawn in respect to generation, acceleration and penetration of electric fields in interplanetary magnetospheres. The study connecting bulk flow velocity and electric field clarified that in a given plasma, it is the bulk flow that produces electric field and not vice versa (Vasyliunas, 2001). The general result in that context could also be derived by conserving the total linear momentum. Also the inductive electric field produced by relaxation of magnetic field lines play an active role in dynamics of inner magnetosphere by accelerating the particles. In the direction parallel to electric field, particles traveling at low latitudes are subjected to prominent equator-oriented acceleration due to the rapid direction-changing $\mathbf{E} \times \mathbf{B}$ drift. This centrifugal effect leads to focusing of ions with small parallel speeds into the equatorial region, which in turn yields the development of substantial (a few kV) parallel potential drops and the production of magnetic field-aligned electron beams (Delcourt, 2002 and references within).

Relativistic outflows are very pervasive in astrophysical scenarios. The propagation of relativistic charged particles in background plasma generate return currents in opposite direction. Interaction between these currents drive various electromagnetic and electrostatic instabilities. The resonant interactions occurring due to Doppler-shifted wave frequency, are shown to be liable of energization of relativistic electrons in outer radiation belts (Horne et al., 2005; Shprits et al., 2006).

Apart from impact on space weather, crucial role played by relativistic particles in transport, acceleration and loss of energy in inner magnetosphere have not been fully investigated. So, motivated from work complied by Friedel et al. (2002), who presented the current state of research into relativistic electron dynamics, covering diffusion, substorm acceleration, wave acceleration etc., we have made an attempt to do numerical analysis of relativistic electromagnetic electron cyclotron harmonics in various magnetospheric regimes.

In space plasma, anisotropic distributions often become skewed, rather than becoming symmetric along the magnetic field. To characterize this asymmetry, Kappa–Maxwellian distribution is used. For the first time, Vasyliunas (1968) showed that suprathermal particles are parameterized by Kappa distribution functions. This Kappa–Maxwellian distribution, which is defined using spectral index 'κ', is actually a product of Maxwellian distribution in perpendicular plane and one-dimensional Kappa distribution along a specific direction in space. In velocity spectrum of plasma particles, the index κ determines the slope of high-energy tails and is generally used in $2 < \kappa < 6$ range. Summers and Thorne (1991) have explained how for a very large value, say $\kappa \to \infty$, Kappa function leads to Maxwellian. It is seen that dispersion properties change significantly in hybrid Kappa–Maxwellian plasma as compared to uniform Maxwellian, bi-Maxwellian or bi-kappa distribution (Hellberg and Mace, 2002; Cattaert et al., 2007). The theory of waves in Kappa distributed plasma was very well investigated by Summers et al. (1994) using kinetic approach. They calculated the dielectric tensor for linear plasma waves in hot plasma with particles parameterized by Kappa distribution function. Work done by Viñas et al. (2005) and Decker et al. (1995) inferred that use of Kappa model resolved the discrepancy between observations and calculations of resonant plasma emissions and echoes used for in-situ measurements of electron density and magnetic field in the magnetospheric environments. Kappa distribution has been found to fit the observations and satellite data of the solar wind (Maksimovic et al., 1997), magnetosphere of Jupiter (Krimigis et al., 1981; Mauk et al., 2004), Saturn (Krimigis et al., 1983; Schippers et al., 2008), Uranus (Krimigis et al., 1986) and terrestrial magnetosphere (Gloeckler and Hamilton, 1987).

The various flyby and orbiter missions, accomplishing the development of technology, have explored the complex and vast magnetospheres of various planets. The data sent by Pioneer, Voyager, Ulysses and Cassini has enriched the space science community in numerous ways. We, therefore mention some of the relevant observations made by Cassini, Voyager 1 and 2 and other terrestrial space crafts to study EMEC instability in magnetosphere of Jupiter, Saturn and Uranus.

1.1. Jupiter

Kurth et al. (1980) first reported the Voyager observations of strong electron-cyclotron harmonic emissions at Jupiter. More plasma waves and radio waves observations were made by Ulysses (Stone et al., 1992) and Galileo (Gurnett et al., 1996) providing opportunity to study magnetosphere of Jupiter in detail. In 1980, Barbosa and Kurth (1980) presented brief encounters with ECH emissions

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