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Theoretical study of electromagnetic electron cyclotron waves in the presence of AC field in Uranian magnetosphere

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HIGHLIGHTS

- Theoretical investigation of electron cyclotron (EMEC) waves in magnetosphere of Uranus, supported by satellite data.
- Temperature anisotropy and energy density of electrons is the main source of free energy.
- Parameters supporting growth are AC frequency and high number density of electrons.
- Minimal presence of energetic particles increases growth rate significantly.
- Parallel propagating EMEC waves grow more than obliquely propagating EMEC waves.

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ABSTRACT

Electromagnetic electron cyclotron (EMEC) waves with temperature anisotropy in the magnetosphere of Uranus have been studied in present work. EMEC waves are investigated using method of characteristic solution by kinetic approach, in presence of AC field. In 1986, Voyager 2 encounter with Uranus revealed that magnetosphere of Uranus exhibit non-Maxwellian high-energy tail distribution. So, the dispersion relation, real frequency and growth rate are evaluated using Lorentzian Kappa distribution function. Effect of temperature anisotropy, AC frequency and number density of particles is found. The study is also extended to oblique propagation of EMEC waves in presence and absence of AC field. Through comprehensive mathematical analysis it is found that when EMEC wave propagates parallel to intrinsic magnetic field of Uranus, its growth is more enhanced than in case of oblique propagation. Results are also discussed in context to magnetosphere of Earth and also gives theoretical explanation to existence of high energetic particles observed by Voyager 2 in the magnetosphere of Uranus. The results can present a further insight into the nature of electron-cyclotron instability condition for the whistler mode waves in the outer radiation belts of Uranus or other space plasmas.

1. Introduction

The Voyager 2 encounter of Uranus in January 1986 provided the opportunity to observe yet another planetary magnetosphere and compare the plasma physical processes taking place there to those occurring in the magnetosphere of Earth. Presence of whistler mode waves, electron cyclotron harmonics along with many more types of waves in the Uranian magnetoplasma, opened a new chapter of study for researchers to explore. The behavior studied for electromagnetic electron-cyclotron (EMEC) waves is of great importance in the electromagnetic emission. Therefore in present paper, EMEC waves have been studied with temperature anisotropy in the magnetosphere of Uranus. EMEC waves are studied by kinetic approach using method of characteristic solution. The kinetic approaches developed may be applicable to laboratory plasma as well as to estimate the heating rates, along with the study of emissions of electromagnetic ion cyclotron waves. Voyager 2 encounter with Uranus revealed that magnetosphere of Uranus exhibit non-Maxwellian high-energy tail distribution. So the dispersion relation, real frequency and growth rate is evaluated using kappa distribution function. Earlier, the anisotropic plasma was modeled with a product-bi-Kappa distribution. The exact numerical values of the growth rates and the instability threshold were derived and contrasted with those for bi-Kappa and a bi-Maxwellian, using plasma parameters and magnetic fields relevant for the solar and terrestrial environments (Lazar et al., 2011). Since non-thermal particle distributions represent non-Maxwellian deviations in the equilibrium, we use Lorentzian Kappa distribution function to evaluate growth rate and real

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frequency of EMEC waves. The study is extended to parallel as well as oblique propagation of EMEC waves. The electron cyclotron emissions represent a useful tool in the diagnostics of fusion plasma and space plasma fluctuations. Results are also discussed in context to magnetoplasma of Earth which gives theoretical explanation to existence of very low frequency (VLF) waves observed by Vogayer 2 in the magnetosphere of Uranus. The results can present a further insight into the nature of electron-cyclotron instability condition for the whistler mode waves in the outer radiation belts of Uranus or other space plasmas.

1.1. Observation at Uranus

The reports on Voyager 2 plasma wave observations during the encounter at Uranus (Gurnett et al., 1986; Kurth et al., 1986) revealed the presence of electrostatic and electromagnetic plasma turbulences, low frequency radio emissions and also non-Maxwellian high-energy tail distribution. Observations of magnetospheric phenomena ranging from upstream ion events to the bow shock and from magnetospheric boundary structures to an intense inner region of hard particles radiation and to a soft magneto-tail plasma sheet were made, but in this paper we refer to the encounter highlights covering plasma waves in inner magnetosphere of Uranus. The analysis of Uranus plasma wave data in the inner magnetosphere was based on wide-band observations and 16-channel measurements covering the range 10 Hz to 56 kHz, which gave details on low frequency radio emissions, electron gyrofrequency harmonics and strong wave activity. Scarf et al. (1987) discussed in detail the characteristics of Uranus waves with frequency (f) less than gyrofrequency (f_c). Their work shows a band of enhanced wave activity with $f = (0.1 - 0.5)\ f_c$. Since the model used by them yielded a high value for electron plasma frequency, it was interpreted as whistler mode chorus and hiss. Also the wave instrument carried by Voyager 2 spacecraft detected a continuous nad of signals with $f < 0.5\ f_c$ during the inner magnetosphere transversal. These waves with fairly steady amplitudes were all whistler mode emissions. The pattern of steady emissions exhibited a distinct break as Voyager transversed the minimum magnetic latitude region. And there was a very great asymmetry in the amplitudes of waves, detected before and after the approach to minimum magnetic latitude region. So at the radial distance of less than 8 R_U strong whistler mode hiss and chorus emissions were observed along with the intense fluxes of energetic electrons. Electron cyclotron waves were also reported in the same region of inner magnetosphere of Uranus (Gurnett et al., 1986). They are believed to be generated by cyclotron resonance interaction with energetic electrons. From the anisotropy produced by the loss cone distribution of trapped electrons, free source of energy comes. Also Hudson et al. (1989) investigated the process of generation of electric field and its magnitude in the range of 1–10 mV/m in the atmosphere of Uranus. Their study concluded that the dynamo-driven magnetic field aligned current in the ionosphere produce plasma instabilities which produces increase in resistivity with a resulting electric field.

Many such observations for other planets with intrinsic magnetic field have been made by several space crafts. Scarf et al. (1979) and Gurnett et al. (1979) provided the details of observations of plasma waves, electron gyrofrequency ranges and energy densities of electron made by Voyager 1 and Voyager 2, respectively for Jupiter magnetosphere. Voyager 2 also observed the first plasma waves for Neptune as electron-cyclotron emissions (Gurnett et al., 1989; Kurth and Gurnett, 1991). Gurnett et al. (1981) reported a series of electro-cyclotron emission bands observed by Voyager 1 inbound leg of Saturn. Scarf et al. (1982) reported again the similar electromagnetic emissions in the inner magnetosphere of Saturn. All these observations were compared by Zarka (2004). Also comparative study of specifically plasma waves of various planetary magnetospheres were conducted by Kurth and Gurnett (1991). Electrostatic electron cyclotron harmonics instability in the magnetosphere of Uranus and other magnetized planets have been investigated using, a particle distribution function which is superposition of cold (Maxwellian) and hot superthermal (Kappa) electrons in conformity with the observations. Normalized temporal growth rates for ECH bands have been calculated (Tripathi and Singhal, 2007).

1.2. Kappa distribution function

Non-thermal particle distributions are found everywhere in solar wind and near-planet space plasma. (Feldman et al., 1975; Montgomery et al., 1968; Maksimovic et al., 1997; Pilipp et al., 1987; Zouganelis, 2008) Such distributions represent non-Maxwellian deviations in the equilibrium. Previous studies have modeled the anisotropic particles with a bi-Maxwellian or a bi-Kappa distribution function and found a suppression of this instability in the presence of suprathermal tails. Solar wind particles exhibit enhanced suprathermal deviations from Maxwellian equilibrium, decreasing as a power law of velocity. They are expected to exist in any low density plasma found in Universe, where binary collisions of charges are rare (Pierrard and Lazar, 2010). So these plasma particle velocity distribution is well explained by the family of kappa or generalized Lorentzian velocity-distribution functions (VDFs):

$$f_i^{\kappa}(r, v) = \frac{n_i}{2\pi(\kappa\alpha_{\kappa i}^2)^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)} \left(1 + \frac{v^2}{\kappa\alpha_{\kappa i}^2}\right)^{-(\kappa+1)} \quad \text{and}$$

$$\alpha_{\kappa i} = \sqrt{(2\kappa-3)kT_i/\kappa m_i}$$

where $\alpha_{\kappa i}$ is thermal velocity, m_i mass of particle of species i, T_i equivalent temperature, n_i their number density, v their velocity and $\Gamma(x)$ is the gamma function. Following the previous work done (Xiao et al., 2007) the instability threshold condition for the kappa distribution decreases as κ increases and tends to the lowest values of bi-Maxwellian as $\kappa \rightarrow \infty$. This is because the velocity space gradients which govern the maximum wave growth are smaller for a kappa plasma than for a bi-Maxwellian plasma. The results by a bi-Maxwellian generally overestimate the maximum wave growth for a kappa plasma. Voyager 2 encounter revealed that natural space plasmas in the magnetosphere of Uranus possess a pronounced non-Maxwellian tail distribution that can be well studied by kappa distributions or VDFs (Kurth, 1992; Vinas et al., 2005). The work in recent past has showed that highly energetic electrons are found to be better fitted by kappa-type distributions (Xiao, 2006; Xiao et al., 2008a). This kappa-type distribution is found to fit very well with the solar energetic particles (Xiao et al., 2008b), and also well with the geostationary orbit electrons (Xiao et al., 2008c). Therefore, in this study we consider energetic electrons modeled with a typical kappa distribution, driving the whistler mode wave instability.

The low energy electrons and ions were measured by low-energy charged-particle (LECP) instrument on Voyager 2. The initial analysis revealed that protons of energy nearly 4 MeV and electrons having energies 1.2 MeV were observed near and within the entire magnetosphere of Uranus (Krimigis et al., 1986). Another detailed analysis of the measurements done by Voyager 2 were reported by Bridge (1986). It shows that for $L > 5$, Uranian magnetosphereic plasma comprises of hot components of few kilo-electron volts. And cold components were observed both inside and outside of $L = 5$ with 4–50 electron volts temperature (Bridge, 1986). Therefore we chose to study electromagnetic electron cyclotron waves driven by energetic electrons of thermal