Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 58 (2016) 1417–1424
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Analytical study of whistler mode waves in presence of parallel DC electric field for relativistic plasma in the magnetosphere of Uranus

R.S. Pandey [a], Rajbir Kaur [b,*]

[a] Department of Applied Physics, Amity Institute of Applied Sciences, Amity University, Sector-125, Noida, U.P., India
[b] Department of Applied Sciences, Guru Tegh Bahadur Institute of Technology, GGS Indraprastha University, New Delhi, India

Received 11 September 2015; received in revised form 18 April 2016; accepted 1 June 2016
Available online 3 June 2016

Abstract

In present paper, field aligned whistler mode waves are analyzed, in the presence of DC field in background plasma having relativistic distribution function in the magnetosphere of Uranus. The work has been examined for relativistic Maxwellian and loss-cone distribution function. In both the cases, we have studied the effect of various plasma parameters on the growth rate of waves by using the method of characteristics and discussed using data provided by Voyager 2. Growth rate has increased by increasing the magnitude of electric field, temperature anisotropy, energy density and number density of particles for Maxwellian and loss-cone background. However, when relativistic factor $\left(\lambda = \sqrt{1 - v^2/c^2}\right)$ increases, growth rate decreases. The significant increase in real frequency of whistler waves can be observed. The results can be used for comparative study of planetary magnetospheres. The derivation can also be adapted to study various other instabilities in magnetosphere of Uranus.

Keywords: Whistler mode waves; Maxwellian distribution function; Loss-cone distribution function; Magnetosphere of Uranus

1. Introduction

Electric fields affect the dynamics of magnetospheric, ionospheric and solar wind plasma. Electric field, when propagating parallel to the magnetic field, transfers energy, mass and momentum by accelerating charged particles to very high energies in auroral regions of the planetary magnetosphere (Hull et al., 2000; Ergun et al., 2001). In 1986, Voyager 2 mission to Uranus, revealed that the planet has an unusual and large magnetosphere. The unique feature is the large value (59°) of angle between Uranus's angular momentum vector and dipole moment vector. So, the spin axis of Uranus is aligned nearly along the planet-sun axis. This leads to the situation that the flow system rotational electric field is oriented in such a way that instead of shielding the middle magnetosphere from the solar wind, it allows solar wind effects to deeply penetrate into the magnetosphere of Uranus (Gurnett et al., 1986). As its consequences, Uranian system permits us to study magnetospheric instabilities. Details of plasma and radiation environment inside Uranian magnetosphere have been discussed by Mauk et al. (1987).

The orientation of planet and its magnetic field control the dynamics of its magnetosphere. Table 1 presents the comparison of some of the specific characteristics of planetary magnetospheres (Bagenal, 1992; Zarka, 2004; Belenkaya, 2009; Hospodarsky et al., 2012 and references therein).

* Corresponding author.
E-mail address: rkaur2@amity.edu (R. Kaur).

http://dx.doi.org/10.1016/j.asr.2016.06.002
0273-1177/

Table 1
Comparison of planetary magnetospheres.

Parameter	Earth	Jupiter	Saturn	Uranus
Distance from Sun	1 AU	5.2 AU	9.58 AU	19.18 AU
Dipole tilt	11.3°	−9.6°	−0.0°	−59°
Obliquity	23.45°	3.12°	26.73°	97.86°
Solar wind density (cm^{-3})	10	0.4	0.1	0.03
Primary sources of plasma	Ionosphere O^+, H^+	Io O^+, S^+	Dione, Tethys O^+, H_2O^+, H^+	H Cloud H^+
Secondary sources of plasma	Solar wind H^+	Ionosphere H	Titan N^+, H^+	Solar wind H^+
Magnetic field	Dipolar	Dipolar	Dipolar	Non-dipolar
Magnetosphere driven by	Solar wind	Rotation of planet	Rotation of planet	Solar wind

Besides being the planet with lowest solar wind density and proton as heaviest particle found in the magnetosphere (Stone et al., 1986; Selesnick and Stone, 1991), maximum dipole tilt of Uranus makes its magnetosphere an exclusive observatory to study growth and damping of waves.

Various types of plasma waves like, Bernstein emissions, whistler waves, radio emissions in Uranian magnetosphere and turbulence in the shock region, were reported by Voyager 2 (Kurth et al., 1988). The low energy charged-particle instrument (LECP) installed on this spacecraft measured protons and electrons have energies to at least 4 and 1.2 MeV respectively (Krimigis et al., 1986). The parallel electric field at Uranus, accelerate these protons and electron. The accelerated particles thus, control wave amplification. Electric fields in direction of magnetic field, can be interpreted using electron pressure gradient effect in the direction of magnetic field, distinguishing between plasmas of different temperature and energies (Hull et al., 2003). One of the major issues of planetary study deal with accelerating charged species to kinetic energy that is much more than their thermal energy initially. Detailed study of upward and downward current regions show that electrons are accelerated by parallel electric field (McFadden et al., 1999; Marklund et al., 2001). The researchers have also shown that parallel electric field amplitudes are uncorrelated with plasma density, remaining uninterrupted with current density (Mozer and Hull, 2001).

In this paper, we confine our investigation to study of waves with frequency lower than electron cyclotron frequency in the magnetosphere of Uranus. The reports discussing the observations made by Voyager 2, show enhanced wave activity at frequency almost 0.1–0.5 times of electron cyclotron frequency. These were interpreted as whistler hiss and chorus by Scarf et al. (1987). Whistler mode hiss has typically been assumed to have limited spectral structure and are found in magnetosphere of Uranus, Saturn, Earth and plasma torus at Jupiter (Gurnett et al., 1981; Scarf et al., 1979; Thorne et al., 1973). However, a recent study by Summers et al. (2014) has revealed that plasmaspheric hiss has complex fine structure with discrete rising tone and falling tone elements. Chorus comprises of many discrete tones that also appear in magnetosphere of Saturn, Jupiter and Earth (Gurnett et al., 1981; Helliwell, 1980). Hiss and Chorus, both are generated by cyclotron resonance interaction with electrons possessing high energies of the order of kilo electron volts (Kennel and Petschek, 1966; Summers et al., 2007; Tao et al., 2012). Due to loss cone type of distribution of electrons, anisotropy is produced which gives rise to free energy source (Gurnett et al., 1986). Therefore, the study of resonant wave-particle interaction among whistlers and electrons are extremely important for deep understanding of planetary magnetospheres (Summers et al., 1998, 2007; Horne et al., 2005).

When wave's Doppler shifted frequency is equivalent to multiples of cyclotron frequency of electrons, resonant wave-particle interactions take place (Stix, 1992). Such interactions energizes relativistic electrons after geomagnetic storm in outer radiation belt (Summers et al., 1998; Horne et al., 2005; Shprits et al., 2006). After those of Earth and Mercury, magnetosphere of Uranus is the third planetary magnetosphere for which substorm activity has been cited (Cheng et al., 1987). And Meredith et al. (2001) have shown in their work that chorus are effective in accelerating electrons to relativistic energies following/during geomagnetic storms. Whistlers are competent of trapping and instantaneous scattering radiation belt particles into loss-cone (Kellogg et al., 2010; Kersten et al., 2011). Test particle simulations results conclude that waves with large amplitude have a tendency to give electrons very high energies while simultaneously scattering those accelerated electrons in loss cone (Cattell et al., 2008; Bortnik et al., 2008). Such results infer that such whistler wave packets in large amplitude radiation belt may lead to sub second increase in relativistic electron precipitation. Two types of electron trapping by whistlers can be studied in literature. First one is trapping of electrons at a fixed phase of the whistler. In this case electrons are considered passing through whistler wave, and then encounter an electric field that rotates along the direction of velocity of electrons (Matsumoto and Omura, 1981; Omura and Matsumoto, 1982). Second one, is trapping of electrons in electrostatic potential of obliquely propagating whistlers (Kumagai et al., 1980). Recent work done by Throne et al. (2013), demonstrates a model of wave acceleration in Earth's radiation belt and confirms that it can be effectively applied to other magnetized planets like Uranus. The model dealt with universal physical process