J. Environ. Nanotechnol.
Volume 4, No.1 (2015) pp. 13-18
ISSN (Print): 2279-0748
ISSN (Online): 2319-5541
doi:10.13074/jent.2015.03.144120

Alfven Wave Instabilities Related with Excess Charge as a Source of Jovian Magnetospheric Micropulsations

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Received: 20.01.2015 Accepted: 07.02.2015 Published: 30-03-2015

Abstract

Hydromagnetic wave instabilities (Alfven wave instabilities, the physical picture of this instability is given in terms of wave-wave interaction) excited by an electron or ion beam passing through IO tours in the Jovian magnetosphere has been studied in the case of low wave frequency and small wave number in the presence of excess charge in the media. It has been obtained that the excess charge near IO has the dominant role in modifying the Alfvan wave instabilities in comparison to the other parameters. The central frequency of this instability is lying within the range of micropulsations for the presence of excess charge of 10^{-3} times the ambient plasma in the Jovian magnetosphere. Hence this excited Alfvan wave instabilities is the one of the possible generation mechanism for the micro-pulsations recorded by Voyager 1 and 2 in the Jovian Magnetosphere.

Keywords: *Alfven wave Instabilities; Wave-Wave Interaction; Jovian Magnetosphere; Micropulsations.*

1. INTRODUCTION

Since the Pioneer work done by Bigg (1964) regarding the remarkable central of the orbital position of Jovian innermost Satellite IO ever the DAM radiation, considerable attention has been given to the explanation of the IO interaction with the Jovian magnetosphere. Voyager 1 flyby in 1979 revealed that IO is the most volcanically active body known in the solar system (Strom *et al.* 1981). The interaction between the Jovian magnetic fields and the rotation of the conducting satellite Io induces currents to flow along the Jovian magnetic field lines was proposed which reach to the polar regions and cause Io-DAM emissions via cyclotron maser instability (CMI) (*Das and Ip*, 2000). DAM emissions involve a considerable number of modulations with durations of less than a few seconds (Litvinenko *et al.* 2009) .For example, modulation lanes can be observed in the dynamic spectra of Jovian DAM emissions (Imai *et al.* 1997; 2002). A modulation lane quenches DAM emissions, and its drift rates are within the range of ±150 kHz s^{-1} (Koshida *et a.* 2010).

Voyager I made first in situ measurements of plasma near IO and found large field aligned currents flowing along with the IO flux tube which indicate the direct evidence of a strong interaction between IO and the Jovian magnetic field (Acuna *et al.* 1981). It is also reported that dense plasma localized in a torus near IO's orbit with a minor axis diameter of about 2 Jovian radii.

The interaction of IO with Jovian radii emissions led quite early to the idea of coupling of plasma near IO with Jovian ionosphere electro dynamically which implies the generation of field aligned currents. The magneto hydrodynamic wave mode that carries field aligned currents is the Alfvan wave. For the Alfvan wave in uniform plasma the group velocity is the magnetic field guided in the plasma rest frame. In the conductor's rest frame given perturbation is swept back by the background flow. The leading edge of the perturbation region lies along the Alfvan characteristics at an angle $\tan^{-1}$ MA to the background magnetic field. MA is the Alfvan Match number. This region is known as Alfvan wings.

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The earlier work reported on the generation of field aligned currents caused by IO's perturbations of Jovian magnetic field assumed that the Jovian and Ionian ionospheres were directly linked by the currents. Computation of the round trip travel time for an Alfvan wave generated at IO, reflected at the Jovian ionosphere and propagating back to IO were less than I_{min}, a time short enough for the Alfvan wave to return to IO before the local plasma could convect past IO. In these unipolar models the Ionian and Jovian ionospheric currents from part of a closed circuit and the conductivity of the Jovian ionosphere directly controls the current flow at IO (Goldreich and Lynden-Bell, 1969; Geertz and Deift, 1973). The local potential jumps were discovered near the DAM source region by (Hess *et al.* 2007b). The Voyager 1 flyby confirmed the presence of the field aligned currents, but the high density and low Alfvan speed of the torus plasma implied a much longer (20 min) round trip travel time for Alfvan waves between the Ionian and Jovian ionosphere. For this much longer travel time Io has moved significantly from its previous position by the time the reflected Alfvan waves arrives and the circuit can not close locally and the current closed some where else in the torus. From the point of view of IO's rest frame the reflected Alfvan wave returns down stream of IO. When Io is near the edge of the plasma torus a direct interaction could still occur (Neubaues, *et al.* 1980) however, when IO is located deeper within the torus, the flow of the plasma past IO produces a local interaction. This would give rise to a particularly complex pattern of waves behind IO as there are certain to be reflections from the Jovian ionosphere also (Gurnett and Geertz, 1981). Walker and Kivelson (1981) found evidence for the existence of current structure on IO's L shell in the Pioneer Io magnetometer data. Recently Wright (1987) has shown that the WKB limit is not valid for IO's Alfvan waves and the waves strongly interact with the torus.The generation mechanism of hydro-magnetic emissions (Micro-pulsations with comparatively short period) have mainly explained in terms of "cyclotron instabilities" (Jacobs and Watanabe 1966). However, in order to explain the long period micro-pulsations by this type of instability, it requires very high energy for beam particles as shown in table, which may implausible from the view-point of the necessary flux. On the other hand, it is not plausible to explain the mechanism of the excitation of such phenomena in terms of the so-called "Alfven wave instability", but we consider the modified Alfven wave instability for the behavior of non neutral plasma beam system to explain the excitation of micro-pulsations.

In this paper we have considered the behaviour of a non-neutral plasma beam system which contains a slight excess charge as a whole for the Jovian magnetospheric conditions. The analysis of this excess system shows that instability can take place at a frequency which is much lower than that of the waves excited by the cyclotron instability can taken place at a frequency which is much lower than that of the waves excited by the ordinary Alfvan wave instability. In section 2 we have established and discuss the mathematical model for the excitation of Alfvan wave due to presence of excess charge in the Jovian magnetospheric plasma. In section 3 we presented our calculations and discussion of the result and have been found that Alfvan wave instability modified by the excess charge present in the Jovian magnetosphere is the one of the dominant generation mechanism for the micro-pulsations observed in the Jovian magnetosphere by Voyager 1 and 2.

Table 1. . Value of Alfvan Velocity with Wave Period

Wave period	MacIlwain's L	Alfven velocity V_A (km/s)	Cyclotron frequency/2π (kHz)	Necessary energy (eV)	
				Proton Beam	Electron beam
10^2 sec	4	700	20	1.07×10^9	1.18×10^9
	7	230	3	6.80×10^6	5.90×10^7
	10	700	2	3.30×10^7	1.18×10^8
10^3 sec	4	700	20	1.07×10^{10}	1.18×10^{10}
	7	230	3	4.10×10^8	5.90×10^8
	10	700	2	1.20×10^9	1.18×10^9

2. MATHEMATICAL FORMULATIONS

The Jovian magnetospheric plasma is considered to be collisionless and consist of an ambient stationary cold plasma and a small fraction of electron beam. Kimura and Matsumote have made full derivation of the sturrock condition of the instability for a low density beam which is suitable for the Jovian magnetospheric condition. By assuming the velocity of the beam as non relativistic it can be obtained very easily that

$$1+\frac{f_e^2}{g_e^2}+\frac{f_i^2}{g_i^2}+\frac{f_b^2}{\gamma g_b^2}\approx\frac{f_i^2}{g_i^2}\equiv\frac{c^2}{v_A^2}\equiv\frac{1}{\beta_A^2} \qquad (1)$$

In which f_e, f_i and f_b are the plasma frequencies for electron , ion and beam respectively. g_e and g_i are their gyro frequencies ; γg_b is the ratio of the beam density to the ambient plasma density; c is the velocity of light, v_A denotes the Alfven velocity which can be expressed as

$$v_A=\frac{B_o}{\sqrt{\mu_o m_i n_i}} \qquad (2)$$

and

$$\frac{f_e^2}{g_e}-\frac{f_i^2}{g_i}-\frac{f_b^2}{g_b}\equiv\frac{e}{B_o\varepsilon_e}(n_e-n_i-\delta n_b) \qquad (3)$$

Here n_b and n_e are the beam and electron numbers; e is the electronic charge; B_o is the intensity of the magnetic field and ε_o is the dielectric constant of free space. If the system is electrically neutral the right hand side of equation (3) will vanishes, otherwise it is not zero. We obtain a relation as follows

$$\frac{f_e^2}{g_e}-\frac{f_i^2}{g_i}-\frac{f_b^2}{g_b}\equiv\frac{f_{ex}^2}{g_b}\equiv-\frac{e}{B_o\varepsilon_o}n_{ex} \qquad (4)$$

The density of the beam in the Jovian magnetosphere is not very high and the given equation is valid

$$f_b^2<<\frac{g_b^2}{\left|\beta_{//}^2-\frac{1}{2}\beta_\perp^2\right|},\frac{g_b^2}{\beta_{//}\beta_A},\frac{g_b^2}{\beta_A^2} \qquad (5)$$

$$f_{ex}^2<<\frac{g_b^2}{2\beta_A^2} \qquad (6)$$

Where $\beta_{//}, \beta_\perp$ ere the parallel and perpendicular velocities of the beam. By applying approximations of Equation (5) and (6) we obtain the relation which is the Sturreck criteria S given below

$$S=\frac{1}{4}\frac{f_b^4 v_{//}^2-g_{ex}^4 v_A^2}{c^2 g_b^2}=\frac{f_b^4}{4c^2 g_b^2}\left\{v_{//}^2-\left(\frac{f_{ex}}{f_b}\right)^2 v_A^2\right\}=\frac{f_b^4}{4c^2 g_b^2}\left\{v_{//}^2-\left(\frac{n_{ex}}{n_b}\right)^2 v_A^2\right\} \qquad (7)$$

We have

$$\omega_o=\frac{1}{2}\left(\frac{f_b^2}{\gamma g_b^3}\beta_A^2\beta_{//}^2+\frac{g_i^2 f_{ex}^2}{g_b f_i^2}\right)$$

$$k_o=\frac{f^2}{2cg_b}\beta_{//} \qquad (8)$$

ω_o is the central frequency and k_o is the central wave number of the instability. Here it shows that the central frequency of the instability is made up of two parts (i) The central frequency of the ordinary Alfven wave instability and (ii) central frequency due to excess charge.

Therefore the condition for excess charge is

$$f_{ex}^2>>\frac{f_b^2}{g_b^2}\beta_{//}^2 \qquad (9)$$

Thus ω_o can be written

$$\omega_o=\frac{\delta}{2}\frac{n_{ex}}{n_i}g_i \qquad (10)$$

The wave frequency ω has its imaginary part unstable is given as

$$\omega_i=\frac{n_b f_i}{2n_i}\sqrt{\beta_{//}^2-\left(\frac{n_{ex}}{n_b}\right)^2\beta_A^2} \qquad (11)$$

This provides us the growth rate of the instability. The frequency given in above equation (11) is same for both proton and electron beams except the sign of the frequency. Therefore the value of ω_o depends upon only the product of ratio n_{ex} / n_i and the ion gyrofrequency g_i electron gyrofrequency. The difference in the sign of ω_o provides the difference in polarization of the excited wave. If the beam is due to electrons ω_o is negative that means left hand polarized excited wave and for protons the excited wave is right hand polarized.

It explains that the transverse component of the beam velocity is not explicitly involved and shows that $v_\perp$ is not essential for this instability. Therefore the component $v_{//}$ plays an important role in k_o and ω_i and in Sturreck criteria for the instability is now written as

If $$v_{//} > \frac{n_{ex}}{n_b} v_A \, or \, v_{//} < -\frac{n_{ex}}{n_b} v_A$$

Non convective instability.

And $-\frac{n_{ex}}{n_b} v_A < v_{//} < \frac{n_{ex}}{n_b} v_A$ evanescent mode in the velocity of (ω_o , k_o)

3. RESULT AND DISCUSSION

The plasma parameters chosen for the Jovian magnetospheric conditions have been taken from planetary ratio astronomy ex/ere, (Warwick et al., 1979) and ion gyrofrequency calculated from the magnetometer experiment (Gurnett et al., 1979). It is possible to compute the Alfven wave scale related to IO if we assume that it is only excited on a field line when it is contact with the satellite. The Alfven speed at the centre of the tours is about 400km/sec which has been obtained from Dessler (1983). The expression of E_z has been plotted in Fig. (1) which is having two terms. The first term depends upon the number density and velocity of the beam which represents the central frequency of the ordinary Alfven wave instability. The second term of the expression can not contribute unless the system has an excess charge. It is clear from the figure that the second term dominates the first term which gives the frequency of the Alfven wave instability. In fig. (2), the related wave length $\lambda_o = \frac{2\pi}{k_o}$ has been plotted as the function of parallel velocity of the beam. It is noted that there is no difference for electron and proton density. In fig (3) the growth rate of the instability is due to the imaginary part of the ω in the unstable region. It shows that increase in beam velocity the growth rate also increases. The domain of the instability and evanescence region has been shown in fig. (4). this figure explains that more excess charges in the system exist, the more beam energy required for non convective instability. In case of the neutral system the non convective instability is excited be any beam which has the velocity more than zero. It is also clear from this plot that the beam density equal to excess charge density manifests a non convective instability if the beam velocity exceeds the Alfven velocity. When the plasma keeps neutrality the conduction current caused by electron drift motion exactly cancels the ion drift motion with in the limits. But the presence of excess charge in the system gives raises the conduction currents by electron and ion drift motion for very low frequency which plays an important role in this instability in the Jovian magnetosphere.

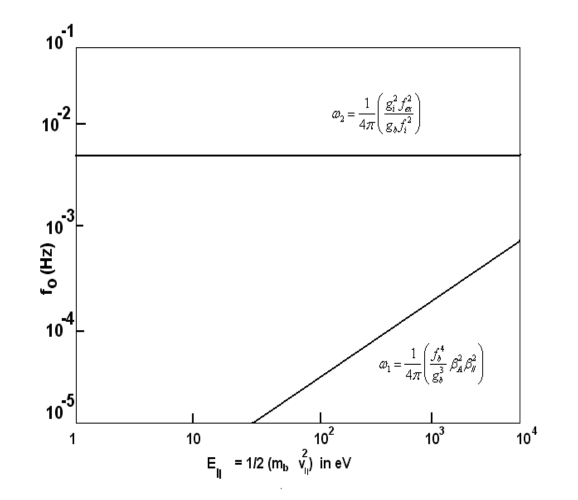

Fig. 1: Variation of the central frequency of Alfven wave instability with the parallel kinetic energy of the beam

To analyze the characteristics of plasma beam system the most useful method is the dispersion relation to discuss the Alfven wave instability for the Jovian magnetospheric condition. Fig. 5 deals the method of solving the dispersion equation, but it has a draw back in which the characteristics of the instability in the vicinity of overlooked. The effect of the beam along the static magnetic field helps us not only in understanding the physical meaning and modified Alfven mode instabilities but also distinctive features of the excess charge system near IO. The modification in the Alfven wave by the beam effect in the low frequency range is due to the presence of excess electron in the Jovian magnetosphere near IO. The evanescent region is reduced due to increase in beam velocity and more increase can leads to the overlapping of newly appeared Alfven mode and the intrinsic Alfven mode resulting in a wave- wave coupling to yield non convective instability. Fig. 6 shows the variation of Alfven match number with the hydromagnetic wave frequencies. The hatched area has been obtained by means of the observation taken by Voyager1. On combination of morphological features of the micropulsations and hydromagnetic wave instabilities recorded by Voyager 1 and 2 during the closest approach of Jupter's magnetosphere, it can be easily concluded that the micro perturbation are excited by these instabilities. The central frequency of instability falls in the range of micropulsations when the Jovian magnetosphere contains excess change to 2 times the ambient plasma density.

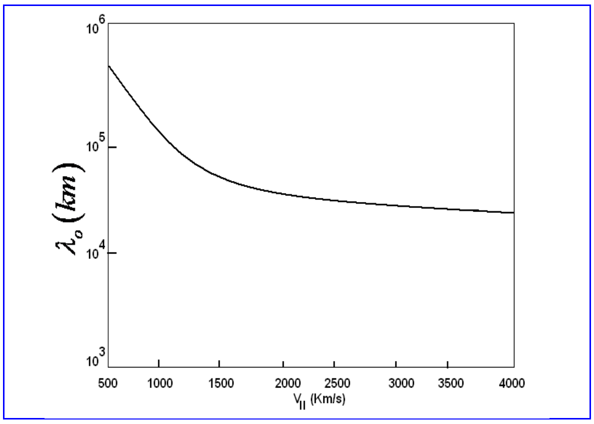

Fig. 2: Wavelength as a function of parallel velocity

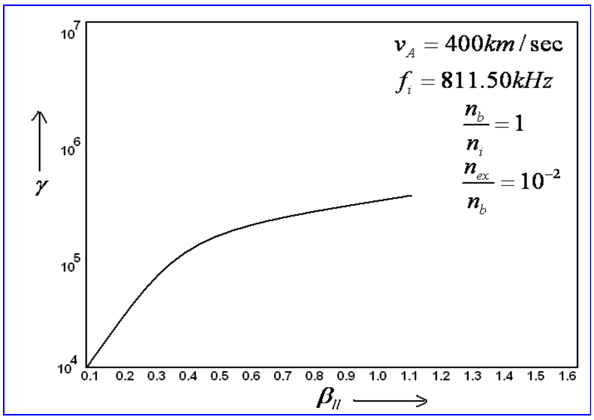

Fig. 3: Plot of growth rate of the excited Alfven wave instabilities with normalized parallel velocity

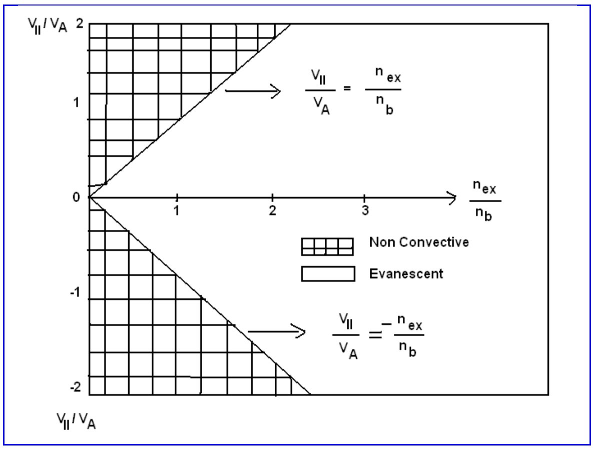

Fig. 4: Illustration of the region of Alfven wave instabilities excited by the presence of excess charge

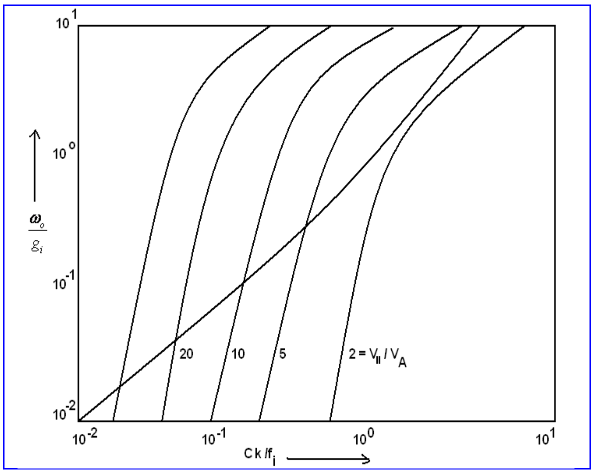

Fig. 5: The illustration of the resonance condition of the Alfven wave near IO

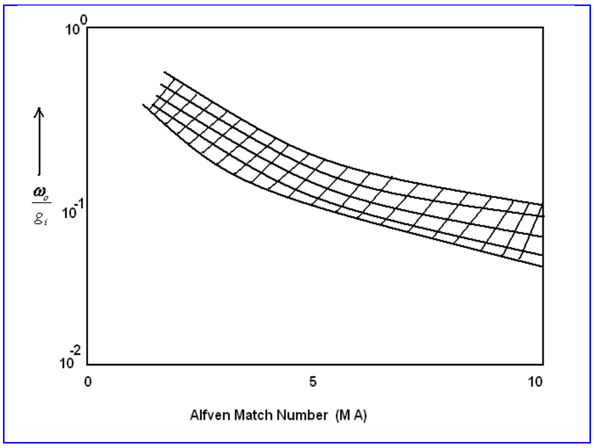

Fig. 6: The variation of the normalized central frequency of the instability with the Alfven Match Number (M A)

According to theoretical analysis the following conclusions about the characteristics if wave instabilities are (1) The central frequency of instability falls in the range of micro-pulsations when the excess charge of the system is taken to be about 10^{-3} times the ambient plasma density, and the ion gyrofrequency around 10 Hz is assumed. (2) The instabilities arise in the Alfven (anisotropic) or modified Alfven (isotropic) mode according to whether the sign of excess charge of the system is negative or positive.

4. ACKNOWLEDGEMENT

The authors are grateful to Director (Prof. Rajat Gupta) NIT Srinagar for his keen interest in this work.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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