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PLASMA-BEAM INSTABILITIES IN COMETARY IONOSPHERES

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ABSTRACT

It is shown that the interaction between the solar wind flux and the cometary ionosphere leads to the excitation of ion sound, whistler, electron-cyclotron, low hybrid and magnetohydrodynamic waves. We investigated the frequency spectrum and found linear-increasing increments and lengths of excited waves.

INTRODUCTION

A cometary ionosphere is separated from the circumfluent solar wind flux around it by a large interim region (10^5 km thick) within which the solar wind plasma and that of a comet are mutually interpenetrating. This system develops plasma-beam instabilities exciting plasma waves of different types.

A wide spectrum of these waves was detected by the ICE-probe that encountered on September 11, 1985 the comet P/Giacobini-Zinner (1984e) plasma tail (*Scarf et al.,* 1986) and ICE, Vega-1,2, Sakigake-probes that passed through P/Halley's head in March 1986 (*Tsurutani,* 1991). The spectra obtained are of a specific type and they are shown by dashes in Fig. 1 (*Tsurutani,* 1991). The maximum on the right corresponds to the ion acoustic waves at the ion Langmuir frequency. Lower in frequencies are whistler mode waves with an intensity maximum at the Low Hybrid Frequency. Finally, ion-cyclotron and magnetohydrodynamic waves materialize as regular fluctuations of the magnetic field are registered in the lowest frequency range. The total energy density of the waves in question can be estimated by measurement data (*Scarf et al.,* 1986) as $1{-}2 \cdot 10^{-13}$ erg/cm^3, which is 0.01% of the solar wind kinetic energy density.

The energy source and the exciting mechanism of the waves in question were investigated by many authors. The plasma-beam instability was studied by *Chernikov* (1974), *Goldstein and Wong* (1987), *Gary and Madland* (1988), *Price and Lee* (1988), and in a number of more recent papers presented in *Tsurutani* (1991). The authors investigated, rather thoroughly, applying analytical and numerical methods, the excitation of ion-cyclotron and magnetohydrodynamic waves that are important for cometary ions acceleration and that can affect shock structure and the cometary ionosphere as a whole. Instability of the remaining higher frequency plasma waves has not been investigated, except by *Chernikov* (1974). He investigated the ion acoustic instability, yet he did not study the strongest hydrodynamic mechanism of instability excitation. The above work focuses the purpose of the present paper, which deals with the whole plasma-beam instability frequency spectrum that occurs under the solar wind and cometary plasma interaction.

THE INITIAL MODEL

We examined an extended region of space where the solar wind plasma and the comet plasma are mutually penetrating. *Scarf et al.* (1986), *Bame et al.* (1986), and *Ogilvie et al.* (1986) indicate that this region consists of the proper transition sheet and the comet sheet whose total thickness (for P/Giacobini-Zinner $\sim 10^5$ km) is much higher than the visual comet cross-section. The plasma parameters and the magnetic field configuration gradually change in the region in question, the cometary plasma density n_o greatly surpassing the solar wind density n_b, throughout the entire region except the outer edge of the transition sheet, with $\alpha = n_b/n_p \ll 1$. Since the characteristic scale of plasma heterogeneities is much greater than the pertinent wavelengths (from tens of meters for ion-acoustic waves up to hundreds of kilometers for magnetohydrodynamic waves), heterogeneity that can affect the development of instabilities can be neglected. Further, we investigated a simple model in which a small density homogeneous plasma beam (the solar wind) interacts with homogeneous cometary plasma.

It should be noted that the relative drift velocity of the two plasmas, V_o, agrees with the relation $V_{Ti} \ll V_o \ll V_{Te}$ where $V_{Ti,e}$ are the ion and electron heat velocities. Thus we deal with a hydrodynamic flux only of the ion plasma component, while the total velocity distribution function of electrons is of a one-hump character. This condition enables us to elaborate a linear theory of the plasma-beam instability.

RESULTS OF CALCULATIONS

A general idea of the results obtained is shown in Fig. 1 (the dependence of instability growth rate γ on frequency ω). We shall consider the spectrum of excitation waves, moving from high frequency waves to low frequency ones.

a) *Langmuir Oscillations:* Plasma-beam instabilities do not excite the oscillations in question, for under the given conditions, instabilities of all types (electron kinetic and hydrodynamic) are inhibited because of high temperature of the flux.

b) *Ion-Acoustic Oscillations:* Their instability is due to the interaction of the solar wind and cometary plasma ion-acoustic waves. There are waves with the frequency $\omega \approx \omega_{pi}$ [where $\omega_{pi} = (4\pi e^2 n_p/M)^{1/2}$ is the cometary ion plasma Langmuir frequency] and the wave number $k \approx \omega_{pi}/V_o$. This brings about the maximum instability growth rate equal to $\gamma \approx \sqrt{3} k V_o \alpha^{1/3}/2^{4/3}$ (*Mikhailovsky,* 1975). For the characteristic values of plasma parameters $n_b = 50$ cm^{-3}, $n_o = 5$ cm^{-3}, $V_o = 100$ km/s we shall obtain $\omega \approx 4.2 \cdot 10^3$ s^{-1}, $\gamma \approx 1.3 \cdot 10^3$ s^{-1}. The ion sound wave length is $\lambda \approx 150$ km.

c) *The Whistler Range Waves* ($\omega_{Hi} < \omega < \omega_{He}$, where $\omega_{Hi,e}$ are ion and electron gyration frequencies): In this range and in lower frequency ones the dispersion plasma properties are essentially affected by the presence of the outer magnetic field $\vec{H}_o$, "frozen-in" the solar wind.

Electron cyclotron oscillations with the dispersion law $\omega \approx \omega_{He} cos\theta$ [where $\theta = (\vec{K}, \vec{V}_o)$, with $\vec{V}_o \| \vec{H}_o$] can be excited due to kinetic instability of the electron flux, as was studied by *Akhiezer* (1974, 6.2). After transforming the equations given for the maximum growth rate, one can get a simple equation $\gamma \approx \alpha\sqrt{\pi/2}\omega_{He}^5 cos\theta sin\theta/(3k^4 V_{Te}^3 V_o)$, valid for $\pi/2\text{-}\theta > \sqrt{m_e/M_i}$. Simultaneously $k = (4/3)(\omega_{He}/V_o)$. With $\theta \approx \pi/2$ the electronic oscillation excitation is more effective on account of the ionic flux hydrodynamic instability, with the growth rate maximum at the Low Hybrid Frequency $\omega \approx \omega_{LH} = (\omega_{He}\omega_{Hi})^{1/2}$ and equal to $\gamma \approx \alpha\omega_{LH}$ with $k = \omega_{He}/V_o$. Assuming $H_o = 20$ nT, we obtain $\omega \approx 20$ s^{-1}, $\gamma \approx 2$ s^{-1}, $\lambda \approx 360$ m. The dependency $\gamma(\omega)$ is given by curve 2.

In this frequency range, faster waves can be excited, whistlers with an electromagnetic character that interact with solar wind ionic acoustic waves. The dependency $\gamma(\omega)$ tabulated from the accurate formula taken from *Akhieser* (1974) $\gamma(\omega)$ is shown in Fig. 1 by curve 3.

d) *Magnetohydrodynamic (MHD) Waves:* Their excitation effectively occurs under cyclotron resonance of the ionic flux (with $\omega \approx kV_o cos\theta - \omega_{Hi}$). A fast magnetosonic wave is unstable (*Akhieser,* 1974) with the dispersion law $\omega = kV_A$ [where $V_A = H_o/(4\pi M_i n_p)^{1/2}$ is the Alfven velocity], the wave number $k = \omega_{Hi}/(V_o cos\theta - V_A)$ and the growth rate $\gamma \approx a^{1/2}\omega_{Hi}$ (see curve 4, Fig. 1). The order of the values gives the following: $\omega \approx 0.4$ s^{-1}, $\gamma \approx 0.7$ s^{-1}, $\lambda \approx 520$ km.

The results obtained give good account of the spectral composition of the radiation observed (see Fig. 1). Moreover, the absolute values of the instability increment of the whistler and MHD-waves are in good agreement with the results by *Price and Lee* (1988) and *Brinca and Tsurutani* (1988), who investigated the excitation of waves by numerical methods.

CONCLUSIONS

The interaction of the solar wind plasma and the cometary ionosphere gets a wide spectrum of the waves that were excited (Fig. 1), namely: ion-acoustic ones with the ion Langmuir frequency , electron-cyclotron ones with the intensity maximum of low hybrid, whistlers and fast magnetic acoustic waves. With this wave energy of about 0.01% the solar wind kinetic energy is produced.

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Fig. 1. The dependence of instability growth rate γ on frequency ω. Curve 1 — an ion-acoustic wave, 2 — electron-cyclotron wave, 3 — whistler, 4 — magnetosonic wave. The dashed line shows the spectral density $I(\omega)$ of radiation that was observed experimentally (*Tsurutani,* 1991).

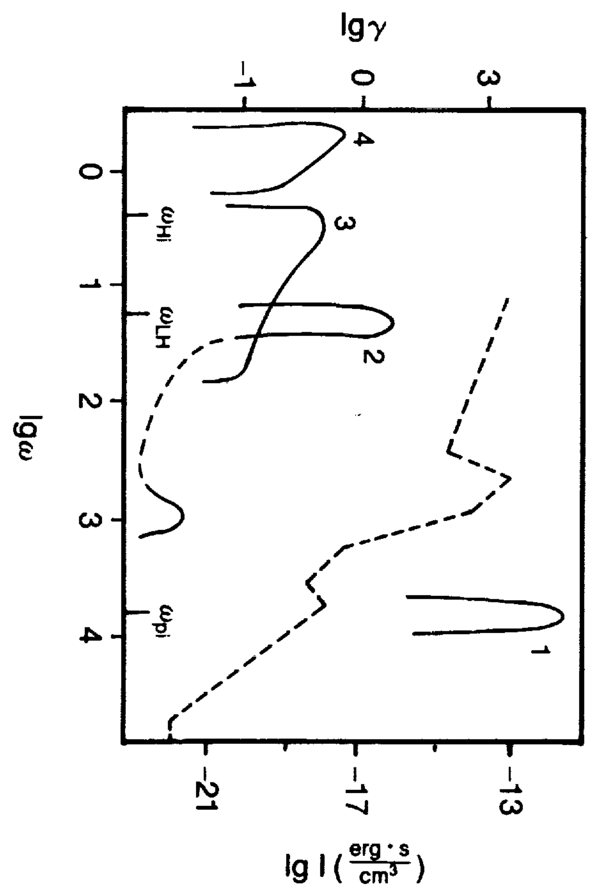

FIGURE 1.