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ABSTRACT

Waves named whistlers, chorus, hiss, saucers and lower hybrid waves are often detected in space plasmas. These emissions are observed between the lower hybrid frequency and the electron gyrofrequency, but are given different names due to properties such as coherence, time duration and polarization. The waves are often classified as either electrostatic or electromagnetic, and are sometimes said to propagate on the resonance cone of the whistler mode. With the aid of dispersion surfaces, plots of frequency versus wavevector components, it can be shown that all these waves often correspond to one wave mode (one single surface). Sometimes the emissions called broadband electrostatic noise also propagate in this mode. Since electromagnetic theory for all angles of propagation relative to the ambient magnetic field is used, the smooth transition between so called electrostatic and so called electromagnetic waves can be described in terms of a gradual change of the wavevector. To give an example of an instability over a wide range of wavevectors, a beam of auroral (keV) electrons is introduced. The highest temporal and spatial growth rates rates caused by such a beam can occur at the plasma frequency. However, a dispersion surface may be used to give some simple arguments showing that in an inhomogeneous plasma, the strongest emissions may occur below the plasma frequency. Furthermore, the significance of the resonance cone is discussed.

INTRODUCTION

Waves named whistlers, chorus, hiss, saucers and lower hybrid waves are often detected in space plasmas. These emissions are usually confined between the lower hybrid (f_{lh}) and electron gyro (f_{ce^-}) frequencies. Another wave phenomenon, which may extend over an even wider range of frequencies, is broadband electrostatic noise. All these waves are labelled with different names due to properties such as coherence, time duration and polarization. Furthermore, the emissions are often classified as either electrostatic or electromagnetic, depending on whether the wave magnetic field can be detected or not. Thus, from observations it may seem as if there are several wave modes between f_{lh} and f_{ce^-}. One main purpose of this report is to show that the waves in this frequency region often correspond to one single wave mode. To provide the readers intuition with a picture of this mode, plots of frequency versus wave vector components (dispersion surfaces) are used (André, 1985).

Dispersion surfaces may be used also to investigate the details of the generation of waves. One of the models in this report describes a plasma where the plasma frequency f_{pl} is lower than f_{ce^-}. When a beam of auroral (keV) electrons is included in this model, large temporal and spatial growth rates are found near f_{pl}. However, with the aid of a dispersion surface, some simple arguments show that the strongest emissions often should be expected below f_{pl}.

Waves above f_{lh} are often said to propagate on the resonance cone of the whistler mode. This cone may be thought of as a cone in real space (Fisher and Gould, 1971), but in the following the term is used to name a region in frequency-wave-vector space. Thus the resonance cone can be found on our dispersion surfaces. Natural emissions which propagate on the resonance cone, are usually not significantly different from waves in other regions of wave-vector space. However, emissions in space plasmas are usually different from monochromatic waves emitted from a point source, which can cause very large energy densities when they propagate on the resonance cone.

THEORETICAL METHOD

In order to study the wave mode of interest, we model the plasma and solve the dispersion relation by numerical methods. The particle distribution funtion F in a model may consists of several particle components,

$$F = \sum_i n_i (\pi^{1/2} v_i)^{-3} \exp[-(\frac{v_z}{v_i} - v_{Di})^2] \exp[-(\frac{v_\perp}{v_i})^2]$$

Here n_i is the density, $v_\perp$ and v_z are the velocity components perpendicular and parallel to the ambient magnetic field $\mathbf{B}_0$, v_i is the thermal velocity, while v_{Di} is the drift velocity along $\mathbf{B}_0$ normalized to v_i. All numerical results in this report are obtained with the computer code WHAMP (Rönnmark, 1982; 1983) which solves the dispersion relation of linear waves in a homogeneous, non-relativistic and collisionless plasma in a uniform magnetic field $\mathbf{B}_0 = B_0 \cdot \mathbf{z}$ for a complex frequency $f+i\gamma$ as a function of real wavevector $\mathbf{k} = k_\perp \cdot \mathbf{x} + k_z \cdot \mathbf{z}$. Both electrostatic and electromagnetic waves are considered and waves occuring in a cold plasma as well as those dependent on thermal effects are included.

WHISTLERS, HISS, CHORUS, SAUCERS AND LOWER HYBRID WAVES

We now consider waves between f_{lh} and f_{ce^-}. Such waves can be found in many regions of space. The parameters in our example of a plasma model (given in the caption of Fig. 1a) are typical for the dayside magnetosphere near geostationary orbit, where f_{ce^-} is larger than f_{pl}. In fig. 1a we display the frequency f normalized to f_{ce^-} versus wavevector components normalized to $1/\rho_{H^+}$, the inverse of the Larmor radius of the protons. There is no source of free energy in this plasma model, so all waves are damped. Heavily damped waves are excluded from the plot, and thus the surface has an edge for finite $|\mathbf{k}|$. Fig. 1a shows only one of the modes which exist in this plasma, and a more complete study is given by André (1985).

The dispersion surface in Fig. 1a can be used to identify several waves which are labelled with different names. It is well known that whistler waves can be found for nearly parallel propagation. ($k_\perp << k_z$). Waves propagating at rather large angles relative to B are also sometimes called whistlers. Emissions which correspond to the surface in Fig. 1a may also be denoted e.g. chorus or hiss. Chorus is more coherent than hiss, but both types of waves correspond to the same wave mode (i.e the same dispersion surface). The emissions may be called electromagnetic or electrostatic, depending on whether the wave magnetic field B can be detected or not. This does not indicate that the waves correspond to different modes. Rather, the smooth transition between so called electrostatic and so called elecrtomagnetic waves can be described in terms of a gradual change of the wavevector. For parallel propagation the surface in Fig. 1a corresponds to circularly polarized waves with a significant B-field, while emissions with $k_\perp >> k_z$ are nearly linearly polarized with a very small wave magnetic field.

Some emissions in space plasmas often show a lower cut off at the lower hybrid frequency, e.g. saucers (James, 1976) and so called lower hybrid waves (e.g. Kintner and Gorney, 1984). Furthermore, some studies of hiss include reflections at f_{lh} (e.g. Huang et. al., 1983). In Fig. 1b we display the same dispersion surface as in Fig. 1a, but we now use a logarithmic frequency scale so the lower hybrid frequency at $f \approx 0.02 f_{ce^-}$ can be seen clearly. Several dispersion surfaces can be obtained from the considered plasma model, but Fig. 1b shows the only surface which for a wide range of $k_\perp$ extends down to, but not below, the lower hybrid frequency (André, 1985). This indicates that the discussed emissions often can be described by the single dispersion surface in Fig. 1b. From the proton gyrofrequency f_{cH^+} up to about $2f_{lh}$ so called ion Bernstein modes may be important at small k_z, but are not shown in our figures (e.g. André, 1985). These modes may explain why the lower cut off at f_{lh} in some cases is absent (e.g. James, 1976). Ion Bernstein modes may also cause finestructure above f_{lh}, e.g. in downgoing auroral hiss (Gorney et. al., 1982).

BROADBAND ELECTROSTATIC NOISE

Auroral hiss can sometimes gradually change into a wave phenomenon called broadband electrostatic noise (BEN) (Gurnett and Frank, 1977). Such BEN emissions have a high frequency cut off near f_{ce^-} and also a lower cut off near or below f_{lh}. Thus BEN sometimes corresponds to the dispersion surfaces in Figs 1a-b. However, other BEN events include emissions which reach frequencies up to a few times f_{ce^-} (e.g. Grabbe and Eastman, 1984). Particle observations show that much energy, e.g. in the form of ion beams, is available during such events. Thus the energy source determines not only the growth rate of the waves, but also the wave propagation properties. Since our dispersion surface is obtained from a model of the non-drifting Maxwellian plasma, it can not be used to describe such events. Still other BEN emissions may be explained by Doppler shift of low frequency turbulence due to spacecraft motion (e.g. Kintner, 1983). Thus, some BEN emissions correspond to the dispersion surface in Fig. 1a-c, while other emissions labelled with the same name can not be explained in this simple way.

THE RESONANCE CONE

Emissions above f_{lh} are often said to propagate on the resonance cone of the whistler mode. To identify the resonance cones in frequency-wavevector space, a contour plot of the dispersion surface in Figs 1a-b is shown in Fig 1c. The resonance cones can be seen clearly when $1 \lesssim k_{\perp}\rho_{H^+} \lesssim 10$. Waves with a certain frequency on a resonance cone, all have a wavevector with a certain direction relative to $\underset{\sim}{B}_0$. Note that the scales of the wavevector components are logarithmic, and thus frequency contours of resonance cones corresponding to different directions of the wavevector relative to $\underset{\sim}{B}_0$, are all parallel. Waves with a certain frequency which are generated on a resonance cone, all propagate at the same angle relative to the ambient magnetic field, thus generating a cone in real space.

Natural emissions in space plasmas often occur over a range of frequencies. Thus a spacecraft moving outside the emitting region observes different frequencies as the angle between $\underset{\sim}{B}_0$ and the line of sight to the source region changes, giving the well known V shape in frequency-time spectrograms (e.g. James, 1976). To an observer inside the emitting region, broadband waves propagating on resonances cones are not significantly different from other waves. The situation is different for monochromatic waves generated by an oscillating point charge. When such waves propagate on a resonance cone, they occur on a single cone in real space. Since all energy is emitted on this single cone, very large energy densities can occur (Kuehl, 1962; Singh and Gould, 1971).

LANGMUIR WAVES AND AN EXAMPLE OF AN INSTABILITY

When $f_{pl}<f_{ce^-}$, the wave propagation properties are somewhat different from those discussed in the previous sections. The wave mode which for perpendicular propagation a lower limit at f_{lh} for a wide range of $k_\perp$, now for parallel propagation stays near f_{pl} for a wide range of k, e.g. André (1985). To give an example of an instability, we consider a model (given in the caption of Fig. 2), which may be used to describe a plasma on auroral field lines at an altitude of 2000-3000 km. A beam of auroral (keV) electrons is also included in the model. Instabilities caused by the positive $\gamma F/\gamma v_z$ of the beam, are indicated by dashed contours on the dispersion surface in Fig. 2. The gap in this surface at somewhat smaller k_z corresponds to damping, caused by the increased negative $\gamma F/\gamma v_z$ introduced by the beam. Largest temporal growth is found at $f\approx f_{pl}$. Thus, when the plasma is homogeneous, the strongest emissions occur near the plasma frequency. Such emissions (with a small wave magnetic field) would be called Langmuir waves. However, the beam appears in a limited region of space, and a wave stops to grow when it propagates out of this region. Thus not only a large γ but also a small group velocity is needed for a wave to grow to large amplitudes. Largest temporal growth rate, smallest group velocity, and

thus largest spatial growth, is obtained near f_{pl}. Thus, when spatial growth is considered, the strongest emissions are still expected near f_{pl}. However, the plasma density varies gradually along the ambient magnetic field. The waves with largest spatial growth rates have their group velocity directed along B_0. When these waves propagate, they must propagate, they must everywhere along the field line fulfill the dispersion relation. This means that the wave for every location along the field line must correspond to a point on the dispersion surface which is obtained for the appropriate plasma density. From Fig. 2 we see that when the plasma frequency increases (decreases), the parallel wavevector component of the wave must decrease (increase) for the frequency to remain constant. For growing waves with a small $k_\perp$ the dispersion surface is flat, and only a small change in plasma frequency is needed for k_z to change so much that damping by the beam (smaller k_z) or Landau damping by the non-drifting electrons (larger k_z) becomes important. For growing waves with $\kappa_\perp$ of the order of unity, much larger changes of the plasma density may occur without changing k_z or the growth rate much. These waves may propagate and be amplified a long way along the field line. Thus, from Fig. 2 we find that when the largest spatial growth rates are found near f_{pl}, the strongest emissions may still occur at much lower frequencies. This is consistent with ray tracing studies of wave propagation in auroral arcs performed by Maggs (1978).

SUMMARY AND DISCUSSION

In this report we conclude that several types of emissions which are named whistlers, chorus, hiss, saucers and lower hybrid waves often all correspond to the same wave mode (the same dispersion surface). Sometimes the emissions called broadband electrostatic noise also propagate in this mode. The names which are in common use may still indicate the region in space where the waves occur, the coherence, the duration and so on. Some of the waves may propagate on the resonance cone of the whistler mode. Natural emissions in space plasmas usually occur over a range of frequencies, and in such cases waves on resonance cones are not drastically different from other waves. However, monochromatic waves generated on a resonance cone by an oscillating point charge, may propagate on a single cone in real space, thus creating very large energy densities. In this report we discuss the resonance cone above the lower hybrid frequency. Similar resonance cones may occur in other regions of frequency-wavevector space, e.g. above the ion-ion (Buchsbaum) frequency in a multicomponent plasma.

In our example of an instability, largest temporal and spatial growth rates occur near f_{pl}. However, a dispersion surface may be used to give some simple arguments which show that the in an inhomogeneous plasma, the strongest emissions can occur below f_{pl}. Our discussion may be extended by considering the spatial dimensions of the beam region perpendicular to $\underset{\sim}{B}_0$. The growing waves just above f_{lh} have a significant $\partial f/\partial k_{\perp}$, and they may leave the a narrow beam region by propagation at a rather large angle relative to $\underset{\sim}{B}_0$. Furthermore, electron beams may destabilize also e.g. ion and electron Bernstein modes and waves near the upper hybrid frequency, which are not considered here.

The dispersion surfaces presented in this report can not be used to understand emissions caused by a very strong energy source. In our first model (Figs 1a-c), no source of free energy is included. In our second model (Fig. 2) an electron beam generates growing waves, but the wave propagation properties are still determined mainly by the non-drifting Maxwellian plasma. Some BEN-events show no cut off at f_{ce}-since the wave propagation properties are determined by the beam causing the emission. Furthermore, in a plasma where a significant amount of the electrons has a temperature which is much higher than the temperature of the cool background electrons, the so called electron acoustic mode may sometimes be important (Tokar and Gorey, 1984). Although no simple theory can explain all wave emissions in a plasma, the dispersion surfaces presented here may be used to organize and simplify the interpretation of many wave observations.

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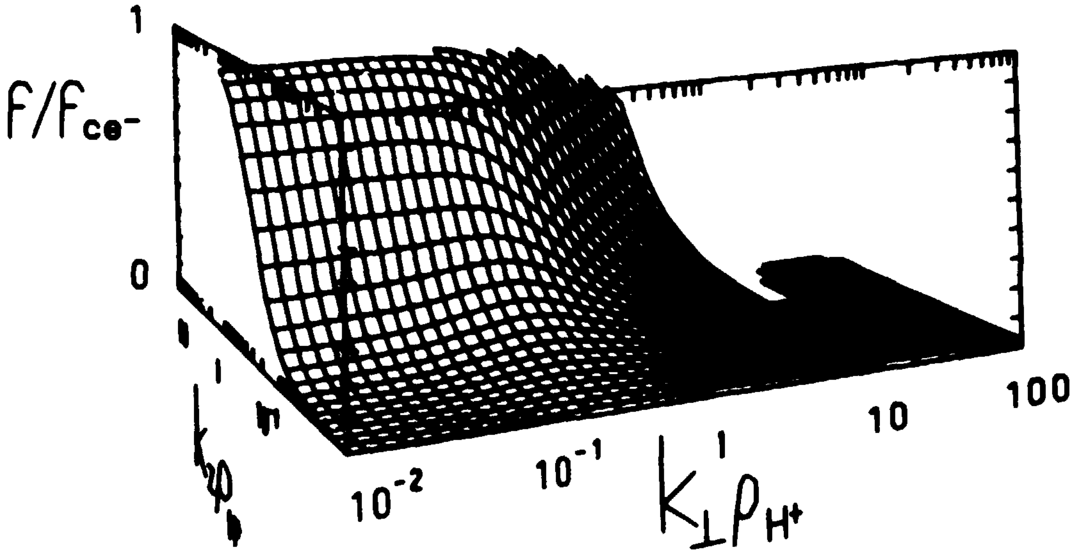

Figure 1a. Dispersion surface obtained with a model which includes one electron and one proton Maxwellian distribution with a temperature of 1 eV and a density of $1.4\cdot10^{6}m^{-3}$ each. The electron gyrofrequency is 3.3 kHz ($B_0=1.2\cdot10^{-7}T$).

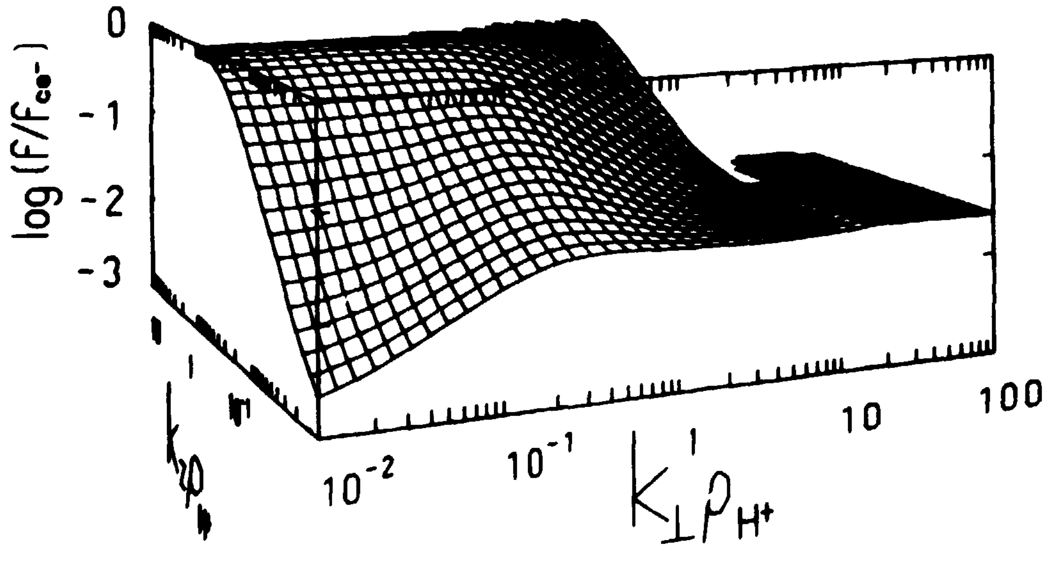

Figure 1b. The same dispersion surface as in Fig. 1a, now displayed with a logarithmic frequency scale. Note that the frequency of this mode approaches zero in the limit of small wavevector.

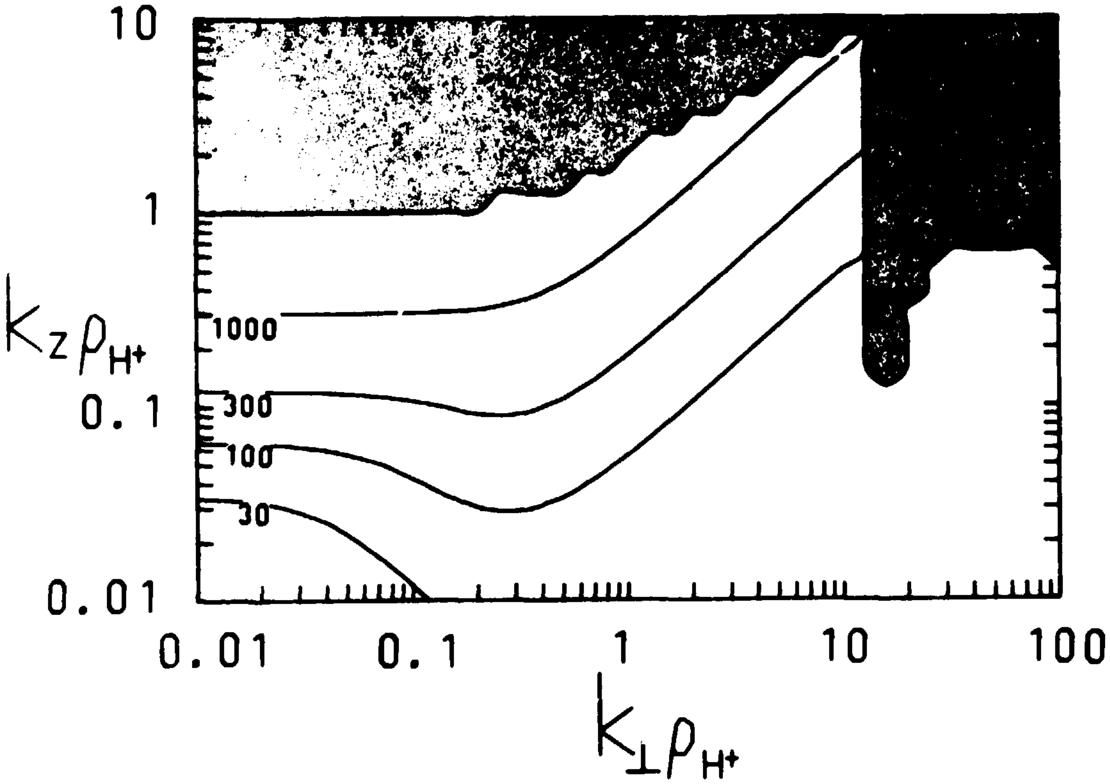

Figure 1c. The same dispersion surface as in Fig. 1a, now displayed in a contour plot. The contours of constant frequency are labelled with multiples of the proton gyrofrequency. Regions of large damping are shaded.

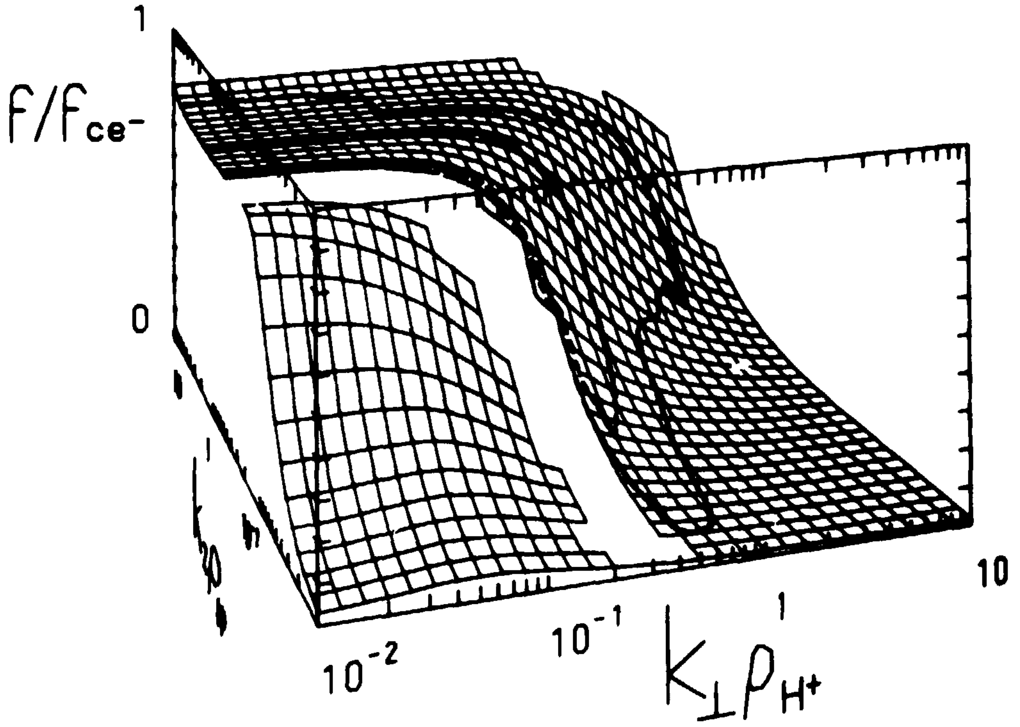

Figure 2. Dispersion surface obtained with a model including proton and electron distributions with densities of $2.5 \cdot 10^9 m^{-3}$ and $2.499 \cdot 10^9 m^{-3}$ respectively, and both with a temperature of 1 eV. Also included is a drifting electron Maxwellian with $n = 10^6 m^{-3}$, a temperature of 1 keV and $v_D = 2$. The contours indicate $\gamma/f_{cH^+} = 10^{-2}$ (outer contour) and 10^{-1}, while the gap in the surface indicates damping.