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Cluster Observations and Theoretical Explanations of Broadband Waves in the Auroral Region

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Abstract

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Broadband extremely low-frequency wave emissions below the ion plasma frequency have been observed by a number of spacecraft and rockets on auroral field lines. The importance of these broadband emissions for transverse ion heating and electron acceleration in the auroral regions is now reasonably well established. However, the exact mechanism(s) for mediating this energy transfer and the wave mode(s) involved are not well known. In this thesis we focus on the identification of broadband waves by different methods.

Two wave analysis methods, involving different approximations and assumptions, give consistent results concerning the wave mode identification. We find that much of the broadband emissions can be identified as a mixture of ion acoustic, electrostatic ion cyclotron and, ion Bernstein waves, which all can be described as different parts of the same dispersion surface in the linear theory of waves in homogeneous plasma.

A new result is that ion acoustic waves occur on auroral magnetic field lines. These are found in relatively small regions interpreted as acceleration regions without cold (tens of eV) electrons.

From interferometry we also determine the phase velocity and k vector for parallel and oblique ion acoustic waves. The retrieved characteristic phase velocity is of the order of the ion acoustic speed and larger than the thermal velocity of the protons. The typical wavelength is around the proton gyro radius and always larger than the Debye length which is consistent with ion acoustic waves.

We have observed quasi-static parallel electric fields associated with the ion acoustic waves in regions with large-scale currents. Waves, in particular ion acoustic waves, can create an anomalous resistivity due to wave-particle interaction when electrons are retarded or trapped by the electric wave-field. To maintain the large-scale current, a parallel electric field is set up, which then can accelerate a second electron population to high velocities.

Keywords: ion acoustic waves, auroral region, anomalous resistivity, Cluster

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List of Papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals.

I. Backrud, M., André, M., Balogh, A., Buchert, S., Cornilleau-Wehrlin, N., Vaivads, A. (2004) Identification of Broadband Waves Above the Auroral Acceleration Region: CLUSTER Observations. *Annales Geophysicae*, 22(12): 14

II. Backrud, M., Stenberg, G., André, M., Morooka, M., Hobara, Y., Joko, S., Rönnmark, K., Cornilleau-Wehrlin, N., Fazakerley, A., Rème, H. Cluster Observations and Theoretical Explanations of Broadband Waves in the Auroral Region. *Annales Geophysicae* (submitted)

III. Backrud, M., Tjulin, A., Vaivads, A., André, M., Fazakerley, A. (2005) Interferometric Identification of Ion Acoustic Broadband Waves in the Auroral Region: CLUSTER Observations. *Geophysical Research Letters* (accepted)

IV. Backrud, M., Backrud, M., Vaivads, A., Wahlund, J-E., Eriksson, A., Buchert, S., Fazakerley, A. Direct Observations of Electric Fields and Particle Acceleration Caused by Anomalous Wave-Particle Resistivity in Space Plasmas. (manuscript)

Contents

1 Introduction

The *Northern Lights* or *Aurora Borealis* is an amazing feature visible on dark polar nights and certainly a memorable feature to experience for a person. The bright aurora has been a subject for both science as well as omens of good or bad things to come. This thesis is about the science, more particularly, about plasma waves in the auroral region. The Earth's closest environment and the Cluster satellite mission are described in the two beginning chapters. The connections between different regions at different altitudes are discussed in chapter 4. Chapter 5 introduces the reader to the concept of plasma and some of the most important parameters involved in space plasmas and in chapter 6 we discuss the theory of waves in plasmas. After the theory part, we can see how plasma waves appear in practice in satellite data in chapter 7. One main focus in this thesis is how to identify a certain type of waves; the so-called broadband extremely low frequency waves and some methods of how to identify these waves are discussed in this chapter. The waves are important in a collisionless plasma because their ability to redistribute energy between, for example, ions and electrons and also because they can carry energy between different locations. In chapter 8 we discuss some possible generation mechanisms for the waves and how they can interact with particles. Finally, in chapter 9, there is a summary of the main results in this thesis and some discussions about what remains.

2 Space

Lovely celestial display! Before your fascinating mysterious play, in which enigmatic forces of Nature flood the heavens with light and color throughout the long Polar night, the golden sunsets of the Pacific Ocean, the gorgeous flora from the Tropics, the resplendent lustre of gems of Golconda, must pale. Lovely celestial display!

Written by Tromholt in his book *Under the Rays of the Aurora Borealis*, 1885

The visible aurora during dark polar nights have fascinated scientists since the days of Galileo but still there are unanswered questions about the causes of the phenomenon. It was also probably Galileo who introduced the term Aurora Borealis, which was the Roman name for the Greek goddess of dawn, Eos. However, the great genius did not yet have any clue of what the aurorae really were. Much before Ørsted, Biot, Savat and Ampère established the relationship between the magnetic field and electric current, the Swedish scientists Anders Celsius and Olav Hiorter reported in 1747 about Hiorter's earlier observations that the magnetic needles in London and in Uppsala reacted to strong auroral displays.


Figure 2.1 Auroral light observed above Uppsala in Sweden [copyright W. *Puccio*]

The visible aurora has a typical spatial scale size from kilometers to the size of the entire auroral oval and can appear in different forms such as arcs, spirals, folds or curls. The emissions are caused by electrons, which have been accelerated by quasi-static electric fields parallel to the geomagnetic field. The precipitating electrons of energies between 100 eV to a few 100 keV collide with ionospheric constituents, and convert kinetic energy into energy stored in the chemically excited states of the ionospheric species. The chemically excited states relax and emit photons of wavelengths determined by the energy transitions in the relaxation processes. The color of the light the visible aurora will appear with depends on what neutral or ionized particle the precipitating electrons collide with. The visible aurora is just the top of an iceberg of incredible underlying plasma processes and couplings between the *magnetosphere* and the *ionosphere*.

2.1 The Magnetosphere

Magnetic fields around our planet act as an obstacle and prevent the solar wind from reaching our Earth. The solar wind streams outward from the sun towards the Earth and decelerates at the *bow shock* in front of the *magnetopause* before it flows through the *magnetosheath*. A schematic view of the Earth's magnetosphere with some important regions indicated is shown in Figure 2.2. The magnetopause is a layer separating the interplanetary magnetic field (IMF) and the geomagnetic field around the Earth and the location of the magnetopause depends on the strength of the solar wind. If it is strong, the magnetopause is pushed closer to the Earth and if the solar wind becomes weaker, the magnetosphere expands and moves the magnetopause further away from the Earth. Generally, the location of the magnetopause is about 10-12 Earth radii (1 R_E = 6371 km) from Earth on the dayside. The protected region inside the magnetopause is called the *magnetosphere* which is filled with plasma originating both from the solar wind and from the *ionosphere* (see section 3.1). The geomagnetic fields are connected to the interplanetary magnetic fields and the solar wind in the so-called *cusp* region, where the solar wind can penetrate the magnetosphere.

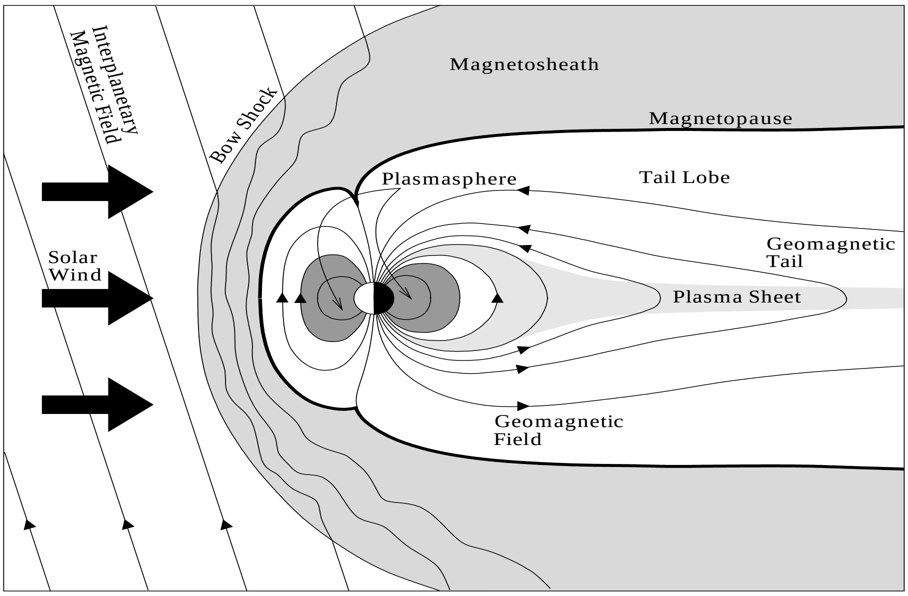

Figure 2.2 A schematic view of the Earth's magnetosphere.

The nightside magnetosphere stretches away from the sun behind the Earth and is called the *geomagnetic tail*. This region of the magnetosphere is important because it acts as a reservoir of energy. The energy can be released into the inner magnetosphere periodically during magnetically disturbed periods called *magnetic substorms.* A current sheet lies in the center of the tail embedded within two regions characterized by hot particle populations and is called the *plasma sheet.* The *north* and *south tail lobes* lie on both sides of the plasma sheet and connect magnetically to the two polar regions of the Earth.

The magnetic field lines in the dayside magnetosphere are closed and nearly dipolar and three major particle populations can be found inside the closed magnetic field lines. The first region is characterized by very energetic ions and electrons and is called the *Van Allen radiation belts*. The particles in the radiation belts are trapped and circle the Earth from about 1000 km above the surface to a geocentric distance of about 6 R_E. The number density and energy density inside the radiation belts are not constant along the field lines and there is not a clear distinction between the radiation belts and another major particle population, the *ring-current-particles*. Most of the ring current is carried by trapped particles, but the terminology "ring current particles" refers to those components of the particle distribution that contribute most to the total current density. The third major particle population in this region is a dense cold particle population in the so-called *plasmasphere*, which coexists in almost the same region as the radiation belts. The plasmasphere is torus-shaped and extends to 3-6 R_E from Earth at the equator.

The layer separating the ionized magnetosphere and the neutral atmosphere is called the ionosphere and extends from approximately 80 km and up to about 1000 km. Both photons from solar radiation and precipitating energetic particles ionize the neutral gas in the upper atmosphere

Magnetic field lines that connect very far away in the magnetotail or connect to the interplanetary magnetic fields are often called *open magnetic field lines* and map to the ionosphere in the *polar cap.* This region is characterized by very low density because of a particle outflow by the *polar wind*.

Particles can be trapped at closed magnetic field lines and the magnetic mirror force will make electrons bounce back and forth between the hemispheres. Electrons generate auroral emissions when they become accelerated by magnetic field-aligned electric fields to such high energies that some of them will overcome the mirror force and penetrate into the ionosphere.

Later in chapter 3.3 and 9 in this thesis, we discuss some theories about what can generate and maintain the vital quasi-static parallel electric field and also suggest a new observed mechanism (paper IV).

3 Magnetosphere-Ionosphere coupling

There are essentially two main ingredients producing the aurora: an acceleration region located at altitudes from a few thousand km up to a few earth radii above the ionosphere, where electrical energy is converted into kinetic energy in the particles and a generator region located far out in the magnetosphere where large amounts of plasma are released and convected towards the Earth.

3.1 The Ionosphere

The conducting ionosphere is the boundary region where collisions between the neutral atmospheric particles and the ionized plasma particles are important. Collisions in the ionosphere allow momentum-exchange between electrons and ions with neutrals and interfere with the free motions of the electrons and ions along the magnetic field **B** and therefore add a resistivity to the currents flowing along **B** in the ionosphere. We will see later in chapter 8.3.2 that a resistivity can also exist in a collisionless plasma.

In a collisionless plasma, the particles are sometimes ruled by the **E** x **B** drifts but in the ionosphere, the collisions cause a break down of the **E** x **B** drift and the disruption allows electrical currents to flow perpendicular to **B** in a response to an electric field **E**. These perpendicular currents are important because they close the magnetic field aligned currents imposed by the magnetosphere.

Figure 3.1 shows a sketch of the **E** x **B** drift processes in the cases of collisionless (top panel) and with ion-neutral collisions present (lower panel). In the top panel, the electrons and ions move with the same time-averaged velocity and there is no current flowing in response to the electric field.

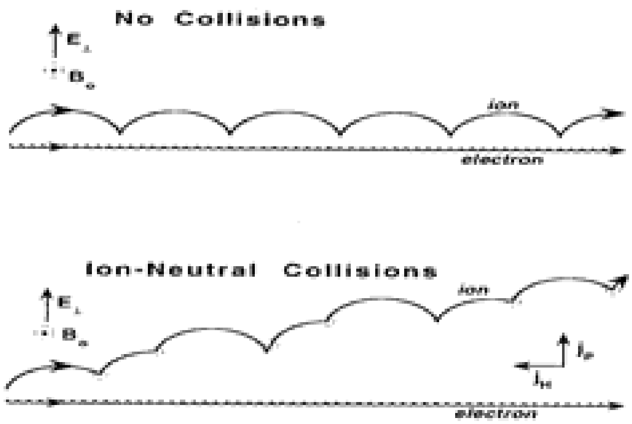

FIGURE 3.1 A sketch of the disruption of **E** x **B** drifts by collisions and resulting perpendicular current. [from *Auroral Plasma Physics, 2002*]

In the bottom panel where collisions between ions and neutrals are present, the ions undergo momentum-exchange in each collision (marked with circles) with the neutral gas, the ions lose the momentum to the neutrals and have to restart their **E** x **B** motion. The ions and electrons will no longer have the same time-averaged velocity and current will flow in response to the electric field. The current component flowing along $E_{\perp}$ is called the Pedersen current and the current flowing in the **E** x **B** direction is called the Hall current.

3.2 Upward and downward current region

The currents in the auroral ionosphere are parts of a large three-dimensional current system coupling the ionosphere to the magnetosphere. One of the main problems in auroral plasma physics concerns the acceleration of the electrons to kinetic energies much higher than their initial thermal energies. Both theory and observations from both the current regions (downward [*Marklund et al*., 2001] and upward [*McFadden et al*. 1999]) have indicated that the electrons are accelerated by parallel electric fields, but the question on how these fields can arise in a collisionless plasma in a self-consistent fashion is still unanswered. In this thesis we only focus on the upward current region.

The precipitating electrons cause the aurora and carry the field-aligned currents in the upward current regions.

To reach the ionosphere, the electrons must have a pitch angle, defined as $\theta = \arctan(v_\perp / v_\parallel)$, where $v_\perp$ and $v_\parallel$ are the perpendicular and parallel components of the electron thermal velocity that is within the so-called loss cone, defined as

$$\theta_{lc} = \arcsin\left(\left[\frac{B_2}{B_1}\right]^{1/2}\right) \tag{3.1}$$

where B_2 is the magnetic field at a certain altitude and B_1 is the magnetic field strength in the ionosphere.

3.3 Parallel electric fields

The importance of parallel electric fields is well established [*Evans,* 1968; *Mozer and Fahleson*, 1970 and *Gurnett and Frank,* 1973] and the theories of the origin of the parallel electric field forming the auroral have numbered at least 22, according to the review study by *Borovsky* [1993]. However, a collisionless plasma has a high parallel conductivity and any parallel electric field should be short-circuited. Some theories show that parallel electric fields can exist in spite of the high conductivity. A simple theory is that when a current is drawn through low-density plasma above the ionosphere, parallel electric fields form and accelerate the electrons to keep current continuity [*Rönnmark,* 1999].

Another theory is that parallel electric fields are associated with shear Alfvén waves [*Goertz and Boswell*, 1979; *Lysak and Dum*, 1983; *Génot et al*., 1999 and *Rönnmark and Hamrin*, 2000].

An additional accelerating mechanism is parallel electric fields set up because of anomalous resistivity caused by waves [*Papadopolous*, 1977*; Hudson,* 1978; *Lysak and Hudson,* 1979]. This is the theory we study in more detail in this thesis and anomalous resistivity is explained in more detail in chapter 8.4.

4 Cluster

This thesis is based on spacecraft observations of the magnetosphere. The observations are made by the *Cluster* spacecraft, which is one of the European Space Agency's cornerstone missions. For the first time, four spacecraft fly in formation orbiting the Earth and can separate time and space of plasma phenomena variations in our magnetosphere. Let us begin with the sad story about what happened to the Cluster I mission. On June 4, 1996, the failure of the Ariane-5 with the four Cluster spacecraft onboard annihilated 10 years of work in less than 1 minute (Figure 4.1).

FIGURE 4.1 Explosion of the first Ariane-5 rocket with the four Cluster spacecraft onboard.

Fortunately, the European Space Agency Science Programme Committee decided to re-build the four Cluster spacecraft again and the spacecraft were launched in the year 2000.

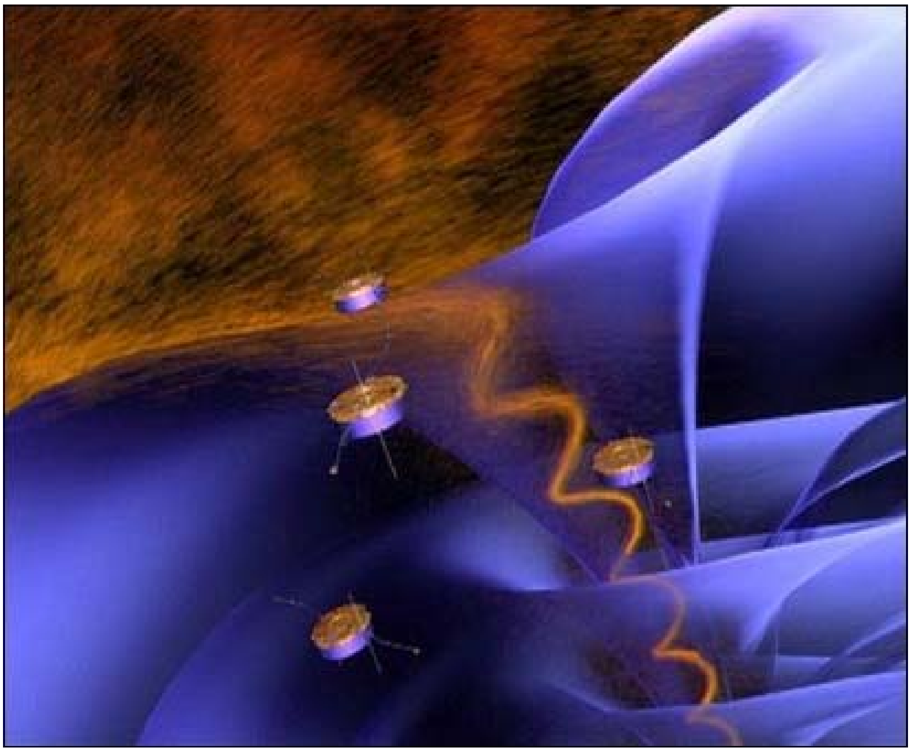

FIGURE 4.2 Artist's view of particles from the solar wind precipitate through the polar cusp and reach the Earth's atmosphere.

The Cluster II mission [*Escoubet et al.*, 1997] was planned as a two-year mission before launch, but has now been in operation for 5 years with an extension to the year 2009. Cluster consists of four cylindrical, identical spacecraft (named Salsa, Samba, Rumba and Tango) with a diameter of 2.9 m, a height of 1.3 m and a total mass of each spacecraft of 1200 kg at launch. In some regions of scientific interest the spacecraft have a tetrahedral configuration with a varying size between 100 km up to 10000 km during the course of the mission. In other regions, for example the auroral region, the spacecraft are instead configured as a string of pearls. Cluster has polar orbits around the Earth with perigee at 19000 km and apogee at 119000 km.

The main scientific objective of the Cluster mission is to study small-scale plasma structures in space and time in the key plasma regions; solar wind and bow shock, magnetopause, cusp, magnetotail and the auroral zone.

4.1 Cluster Instrumentation

Each Cluster spacecraft carries 11 instruments onboard, giving a total of 44 instruments together.

The main instrument used in the papers included in this thesis is the Electric Field and Wave (EFW) experiment [*Gustafsson et al.,* 1997]. This instrument has been designed to study the fast time- and space-varying electric fields and can also measure the spacecraft potential from which the plasma density can be retrieved. The instrument consists of four spherical sensors located at the ends of 44 m long booms in the spin plane of each satellite. There are several other instruments also used for the studies in the enclosed papers. The Spatio-Temporal Analysis of Field Fluctuation (STAFF [*Cornilleau-Wehrlin et al*., 1997]) instrument consists of a search coil and measures the fluctuating magnetic field components. Other instruments used on Cluster are the Flux Gate Magnetometer (FGM [*Balogh et al*., 1997]), The Cluster Ion Spectroscopy instrument (CIS) and the Plasma Electron And Current Experiment (PEACE [*Johnstone et al*. 1997]).

The details concerning the other used instruments can be found in *Escoubet et al*., [1997].

5 Plasma

The plasma state is a charged gas where the atoms are dissociated into negative electrons and positive ions. It has been said that 99% of the visible matter in the universe is in the plasma state. We are surrounded by plasma, both in larger scales as our magnetosphere and stellar interiors, but also closer to us as neon signs or the flash of lightning. Plasma is defined as *a quasineutral gas of charged and neutral particles which exhibit collective behaviour.*

5.1 Plasma parameters

Two fundamental parameters can describe some of the important properties of plasma. The first one is describing the characteristic collective behavior of the charged particles caused by the long-range Coulomb forces. It is called the *Debye length* and is defined as

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}, \tag{5.1}$$

for an electron-ion plasma where k_B is the Boltzmann constant and ε_0 is the permittivity of vacuum. The parameter T_e denotes the temperature and n_e denotes the density of the electrons in the plasma. The Debye length is a measure of the thickness of a sheath in which charged particles interact directly with each other. For dimensions L, larger than λ_D, the particles will instead interact at a distance and averaging over L, the plasma is quasineutral. A criterion for a charged gas to behave as plasma is that it is dense enough so that a sphere with radius λ_D contains a large number of particles.

The other fundamental parameter is the *plasma frequency*

$$\omega_{pe} = \left(\frac{4\pi n_e e^2}{m_e} \right)^{1/2}, \tag{5.2}$$

which is the frequency of the oscillations, essentially determined by the inertia of the electrons, arising when the local charge neutrality is disturbed. The thermal velocity relates the plasma frequency and the Debye length by

$$\lambda_D = \frac{v_{the}}{\sqrt{2}\omega_{pe}} \tag{5.3}$$

where

$$v_{the} = \left(\frac{2KT_e}{m_e e} \right)^{1/2} \tag{5.4}$$

is the electron thermal speed.

5.2 Plasma as a fluid

Plasma in theory can be treated in different ways. An easy method is to treat the plasma as fluid, i.e. one neglects the identity of the individual particle and instead introduces the motion of the fluid elements. Many plasma phenomena can be described by fluid theory. The basic properties of plasma waves treated in this thesis can be described by fluid theory. However, the fluid theory is inadequate to describe the processes involved in the wave studies in this thesis. In particular in this thesis, when accelerated particles have to be taken into account we need a more complicated theory, *the kinetic theory.*

5.3 Kinetic theory

In kinetic theory, we need to consider instead the velocity distribution f(**v**) for each particle species. A main difference in fluid and kinetic theory can be understood by considering two velocity distributions $f_1(v_x)$ and $f_2(v_x)$ in a one dimensional system. The two velocity distributions are displayed in Figure 5.1 and we can see that they have entirely different shapes, but as long as the areas under the curves are the same and the drift velocity is the same, fluid theory cannot distinguish between them while kinetic theory can.

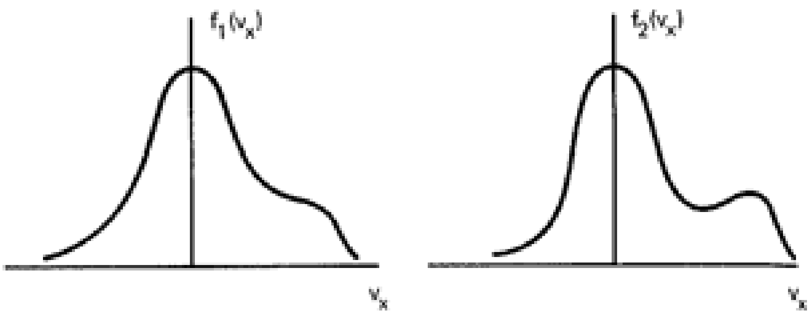

FIGURE 5.1 two examples of velocity distributions $f_1(v_x)$ and $f_2(v_x)$ in a one dimensional system.

More about both fluid- and kinetic theory can be read in textbooks (*Kivelson and Russell*, 1997).

6 Waves in Theory

Every day, different types of waves, for example, waves at seas and sound waves, surround us. Waves are important because of their ability to transport energy and information. They are also important in collisionless plasmas such as our magnetosphere, where waves can interact with particles and re-distribute energy between different particle populations.

The common response from a physical system experiencing perturbations is to emit waves. A displacement ψ propagating with the velocity v, in the positive x direction can be described by the formula for a *harmonic wave*

$$\psi = A\cos k(x - vt) \tag{6.1}$$

A is the *amplitude* and the *propagation number* is denoted k and has the dimension of the inverse of the length. The spatial period λ is called the *wavelength* and is related to the propagation number by

$$k = \frac{2\pi}{\lambda} \tag{6.2}$$

When describing the properties of waves, it is often more convenient to introduce the exponential notation $e^{ix} = \cos x + i\sin x$. If we choose the amplitude to be to be real, we can express equation (6.1) as

$$\psi = A\mathcal{R}e^{ik(x-vt)} \tag{6.3}$$

where the argument $x - vt = kx - \omega t$ is called the *phase* of the wave. It is constant if the wave propagates without changing its shape i.e $(d/dt)(kx - \omega t) = 0$, or

$$\frac{dx}{dt} = \frac{\omega}{k} \equiv v_\varphi \tag{6.4}$$

This is called the *phase velocity* of a wave which in plasma often can exceed the velocity of light. However, a long wave train with constant amplitude cannot carry information. It is the envelope of the wave given by $\cos\left[(\Delta k)x-(\Delta\omega)t\right]$ that carries the information and travels at the velocity $\Delta\omega/\Delta k$. Taking the limit $\Delta\omega\rightarrow 0$, we define the *group velocity* to be

$$v_g = d\omega / dk \tag{6.5}$$

6.1 Electromagnetic and Electrostatic Waves

Many types of waves can exist in plasma and it useful to classify them in some way. The most common way is to divide them into extreme cases. In the first case we divide them into *parallel* and *perpendicular* oscillations according to the direction of the wave vector **k** relative to the undisturbed ambient magnetic field $\mathbf{B}_0$. In the other extreme case we divide them into *longitudinal* and *transversal* waves, which refers to the direction of **k** relative to the *oscillating* electric field $\mathbf{E}_1$. If the *oscillating* magnetic field $\mathbf{B}_1$ is zero or small, the wave is *electrostatic*; otherwise, it is *electromagnetic*.

The two extreme cases are explained above, but in reality one can have a **k** vector at an arbitrary angle to $\mathbf{B}_0$ or $\mathbf{E}_1$ and a mixture of the principal modes discussed above. Further on, we will mainly discuss electrostatic waves.

6.2 Dispersion Relations

To be able to study waves we can derive something called a *dispersion relation*, which describes the relation between the frequency f, and the wave vector **k** of the wave. Deriving a dispersion relation can often be very complicated, but a standard procedure is to use the set of equations according to fluid theory, assume small amplitude waves and linerize the plasma equations by neglecting all higher order terms. To simplify things the time and space varying quantities can be replaced according to

$$\begin{aligned} \frac{\delta}{\delta t} &\rightarrow -i\omega \\ \nabla &\rightarrow i\mathbf{k} \\ \nabla\cdot &\rightarrow i\mathbf{k}\cdot \\ \nabla\times &\rightarrow i\mathbf{k}\times \end{aligned} \qquad (6.6)\text{-}(6.9)$$

The angular frequency ω is assumed to be complex, while the wave vector **k** is real. By doing these replacements we can rewrite Eq. 6.1

$$e^{-i\omega t} = e^{\gamma t} e^{-i\omega_r t} \qquad (6.10)$$

where ω_r is the real part of the angular frequency. The imaginary factor, $e^{\gamma t}$ indicates exponentially growth or decay with time of the wave. If $\gamma<0$, the wave is decaying and losing energy to particles while if $\gamma>0$, the wave is growing which indicates that the wave instead is extracting energy from particles in the surrounding plasma.

6.3 Ion waves

An ordinary sound wave cannot occur in the absence of collisions. In plasma, ion acoustic waves can occur through the charge of the ions, electrons and the intermediary electric field. These waves will be low-frequency oscillations because the motion of the massive ions is involved. Ways to derive the dispersion relation for ion waves according to fluid theory can be found in many textbooks (*Kivelson and Russell*, 1997) and is given by

$$\frac{\omega}{k} = \left(\frac{\gamma_e KT_e + \gamma_i KT_i}{M}\right)^{1/2} \equiv c_s \qquad (6.11)$$

This is the dispersion relation for *ion acoustic waves* where c_s is the speed of sound in the plasma and M is the mass of protons. The electrons move fast relative to these waves which is why they have time to equalize their temperature everywhere, therefore, the electrons are isothermal and $\gamma_e = 1$. We have assumed plane waves so the ions suffer one-dimensional compressions, $\gamma_i = 3$ in this case. Ion acoustic waves forms from regions of compression and rarefaction where the regions of compression tend to expand into rarefactions for two reasons. The first is that the ion thermal motions spread out the ions, which is described by the second term in Eq (6.11). The second reason is that the ion bunches are positively charged and tend to disperse because of the resulting electric field. To a large part, the electrons shield this electric field out and only a fraction, proportional to KT_e, is available to act on the ion bunches and is described by the first term in Eq (6.11). The ions overshoot because of their inertia and the compressions and rarefactions are regenerated to form a wave. The error introduced in c_s because of using fluid theory is of order $k^2\lambda_D^2$ (see textbooks). As long as the shortest wavelengths of the waves are larger than λ_D, the plasma approximation made in fluid theory is valid. The upper frequency limit for an ion acoustic wave is the ion plasma frequency, but the condition $k_{\parallel}^2 c_s^2 << 1$ is violated well before this upper limit is reached.

When **k** gets more perpendicular to $\mathbf{B}_0$, the ions undergo an acoustic-type oscillation, but the Lorenz force constitutes a new restoring force giving rise to another term, *the cyclotron frequency* Ω_c^2. This gives a dispersion relation for *electrostatic ion cyclotron waves*

$$\omega^2 = \Omega_c^2 + k^2 c_s^2 \quad (6.12)$$

6.4 Dispersion Surfaces

It can be hard to understand the properties of different wave modes and how they are related to each other only by deriving the dispersion relation. Plotting the solutions to the dispersion relations in three dimensional *dispersion surfaces* plots (f, $k_{\parallel}$, $k_{\perp}$) for a given plasma model helps in understanding. Figure 6.1 shows dispersion surfaces of linear waves in collisionless and homogeneous plasma. The original figure can be found in André [1985].

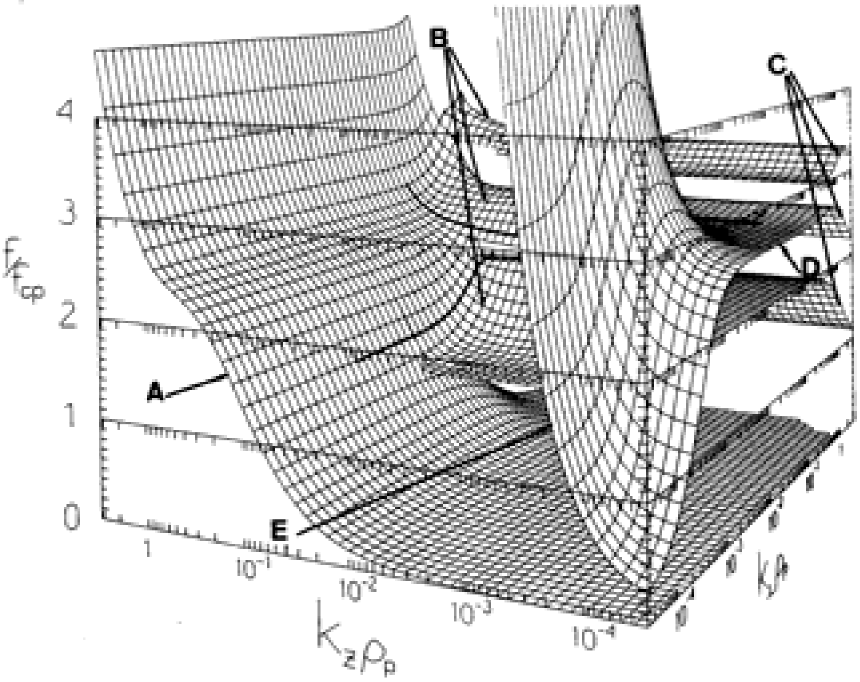

FIGURE 6.1 Dispersion surfaces in a plasma with includes electron and proton distributions with temperatures of 1 keV and 2 eV respectively and with a density of 1.5 cm^{-3} each. The geomagnetic field-strength is $7 \cdot 10^{-6}$ T.

The surfaces are numerically calculated by a computer code called WHAMP [*Rönnmark*, 1982] which solves the dispersion relation using kinetic theory for linear waves in a homogeneous magnetized plasma. The model in this figure consists of a proton component with temperature 2 eV and an electron distribution with temperature 1keV with a density of 1.5 cm^{-3} each. The geomagnetic field-strength is $7 \cdot 10^{-6}$ T. The frequency axes are normalized by the proton gyro frequency f_{cp} and the wave vector components k_z (earlier denoted $k_{\parallel}$) and $k_{\perp}$ are multiplied with the proton gyro radius ρ_p to obtain dimensionless axes. The surfaces, or parts of them are labeled with capital letters and we will now discuss a few of them in more detail. However, there is no consensus among scientists on the nomenclature concerning waves.

The letter A shows the region where the ion acoustic wave propagates. The region forms from strictly parallel propagation ($k_{\perp}$=0) into propagation around 45 degrees ($k_{\parallel} / k_{\perp} = 1$) where the influence from the ambient magnetic field is strong and the mode is not called ion acoustic waves any more. The waves are often called *slow ion acoustic waves* if they propagate in the same region (~45 degrees) but below f_{cp}

The waves in region B are the banded electrostatic ion cyclotron wave mode and C is often called *Ion Bernstein waves*.

In reality when spacecraft and rockets observe electrostatic plasma waves in the auroral region, there is often a mixture of the above-mentioned wave modes and many of them at auroral magnetic field lines, are broad in the frequency range.

7 Waves in Practice

To do in situ measurements of a plasma to study the ongoing processes is one way to go when chasing the “truth out there”.

In this thesis we focus on identifying the waves observed in the auroral region. Not before the waves are identified, is it possible to put them into a larger perspective and determine what kind of skills they have and in what surrounding plasma they can exist. So, what kind of waves are we observing and how can satellite observations be analysed to find the wave vector?

7.1 Broadband Extremely Low Frequency Waves

Most of the waves observed at auroral magnetic field lines are broadbanded in frequency and their power spectral densities decrease with increasing frequencies. These waves are called *Broadband Extremely Low Frequency Waves* or *BB-ELF waves.* What wave modes the BB-ELF waves consist of is one of the main focuses in the enclosed papers in this thesis. If identification of the waves is possible, it is easier to put the broadband waves into a larger picture concerning energy exchanges with particles and so on.

Figure 7.1 shows a typical plot of broadband waves observed by the Cluster spacecraft and the next section will reveal some of the secrets of how to identify these BB-ELF waves.

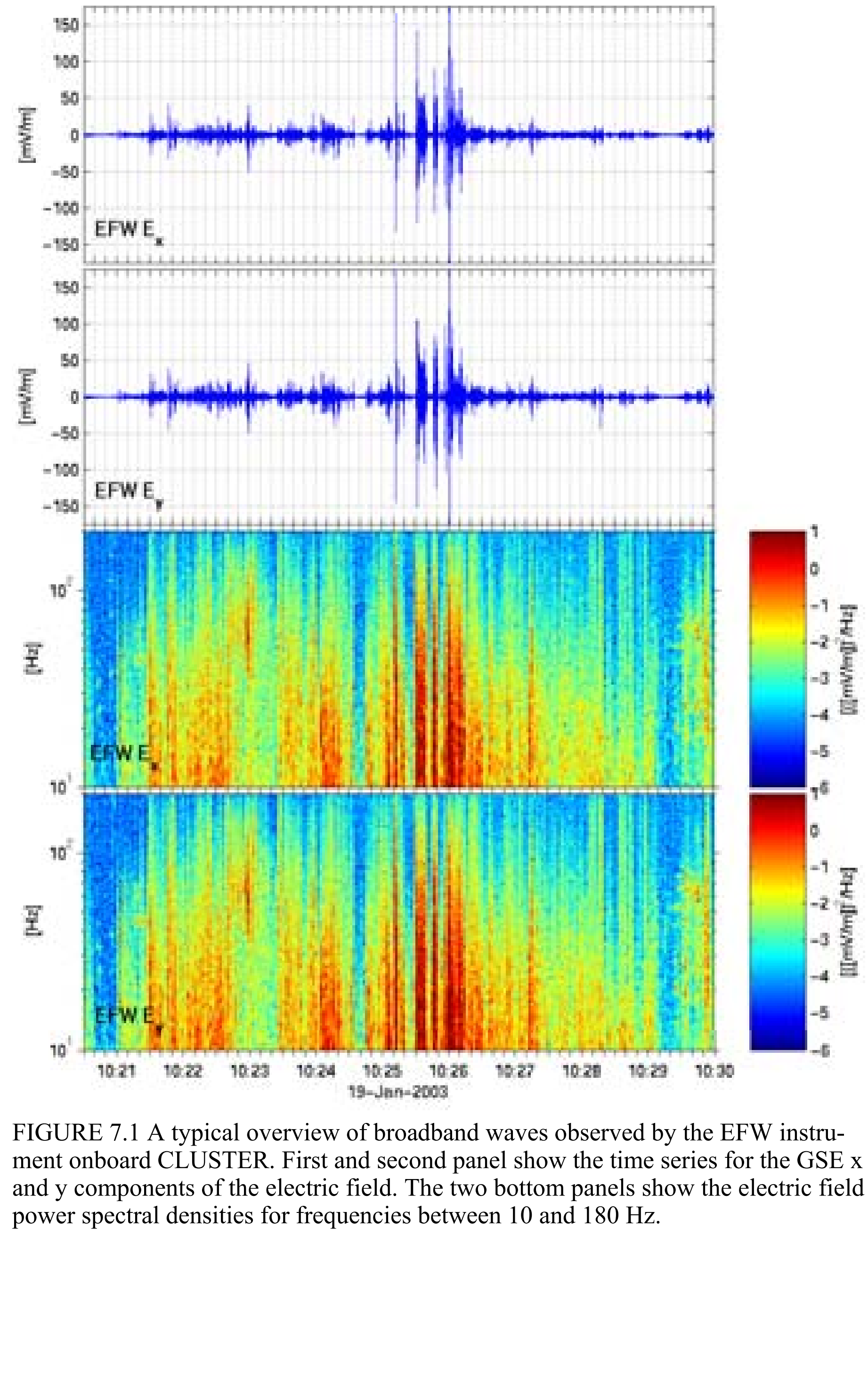

FIGURE 7.1 A typical overview of broadband waves observed by the EFW instrument onboard CLUSTER. First and second panel show the time series for the GSE x and y components of the electric field. The two bottom panels show the electric field power spectral densities for frequencies between 10 and 180 Hz.

7.2 How to identify the wave modes in BB-ELF waves

As we could see in Figure. 6.1 the dispersion surface was changing in parallel and perpendicular (to the geomagnetic field) directions and also in frequency. First we can determine that the observed waves studied in this thesis are electrostatic since the E/B ratio is well above the speed of light. According to theory for an electrostatic wave, the electric field is nearly parallel to the wave vector **k** and we can divide the measured wave electric field into a parallel and a perpendicular component and get a hint of the wave vector of the wave in relation to the geomagnetic field. This is probably the simplest way to get a clue of the wave mode. Further information about the waves can be retrieved by also studying how the ratio between the electric and magnetic field fluctuations varies in parallel and perpendicular directions, i.e. study the *polarization* of the wave. This ratio can be compared to theory, solving the dispersion relation and see how the polarization varies in theory for different wave modes. However, to solve the dispersion relation one has to set up a realistic plasma model first which consists of information about the geomagnetic field and particle populations estimated from observations. This method is used in paper I, and II in this thesis.

Another, way to get a hint of the **k** vector is to use *interferometry*, which is used in paper III in this thesis. In this method you use the fact that some instruments do simultaneous measurements of a wave parameter at distinct points and it is possible to study the phase difference of a wave when it passes the distinct points. Knowing the distance between the point measurements and assuming plane waves with a wavelength longer than the separation distance; one can estimate the wave vector for the wave.

On each Cluster spacecraft, there are four probes measuring the potentials (from which we can retrieve the electric wave field) and we can therefore estimate the projection of the **k** vector in that plane, the spin plane. However, you can only do this type of analysis from the EFW instruments when they are run in so-called *internal burst mode*. This is the only time data from each individual probe is available. The available amount of internal burst mode data during one Cluster orbit is around 20 seconds of data.

8 Wave-particle interactions

Wave-particle interactions play an important role in plasma dynamics and result in exchanges of energy and momentum between waves and particles. These processes can go both ways, either the particles give energy to the waves, which generate wave instability, or the wave gives energy to the particles where so-called *ion conics* is one example. There are also particle-particle interactions in the presence of an intermediary electric wave field that give rise to pseudo-resistivity also called *anomalous resistivity.*

8.1 Electron-beam driven ion acoustic instability

The left part in the sketch displayed in Figure 8.1 shows a bulk current flow of hot electrons with the drift velocity v_d while the ions are cold. We assume that the thermal velocity of the electrons is much larger than their drift velocity, $v_d << v_{the}$ (otherwise we would get another instability, the so-called Buneman instability). From inspection of Figure 8.1 we see that instability can arise in a restricted range of wave phase velocities ω / k . Instability can arise as long as the background ion thermal velocity is smaller than the phase velocity, $|\omega / k| >> v_{thi}$ and in order to escape Landau damping, it must also fall within a positive slope in the electron distribution function.

8.2 Ion-beam driven ion acoustic instability

The right part of Figure 8.1 shows the same cold ion distribution together with a hot, slightly shifted electron distribution and an ion beam with drift velocity v_b along the ambient magnetic field. Up-going beams of this kind are often found in the auroral ionosphere and in the magnetosphere above, during disturbed conditions due to substorms.

Instability can arise in the positive slope of the ion beam distribution function, but in order to escape electron Landau damping, the phase velocity must be far enough from the thermal electron distribution or where the electron distribution function is almost flat.

The conditions for ion beam-instability are the same as for the electron beam-instability if one replaces the current drift speed with the ion beam velocity. The ion beam-driven instability is weaker than the current-driven ion acoustic instability (i.e. the ion beam instability growth rate is smaller by the ratio of beam to plasma densities, see *Treumann and Baumjohann,* [1997]).

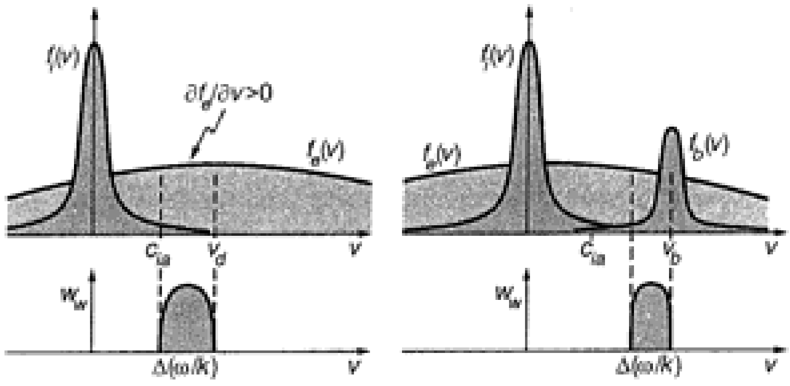

FIGURE 8.1 Ion acoustic-unstable velocity space distributions [*Advanced Space Plasma Physics,* 1997]

8.3 Ion conics

The heating of ion conics is one example of energy going from waves to particles. Heated ions with typical energies of a couple of eV to a few keV have been observed by rockets [*Kintner et al.,* 1992] ans by satellites [*André and Chang,* 1993; *Sauvaud et al*., 2001]. Ionospheric ions get perpendicularly heated through wave-particle interactions and move up along the field lines. The heated ions will evolve into so-called ion conics with an anisotropic, conical space velocity distribution because of the mirror geometry of the magnetic field.

Waves from below the ion gyro frequency [*Hultqvist,* 1996] and up to the lower hybrid frequency [*Chang and Coppi,* 1981] are the most efficient waves in transversely heating the ions.

8.4 Anomalous resistivity

Resistivity due to collisions was discussed earlier in section 3.1 but the magnetosphere is collisionless and a resistivity can instead be generated by waves and is called *anomalous resistivity*. The idea for anomalous resistivity is that when wave instability occurs in regions where there is a large-scale current, such as in the upward current region (section 3.2), the current carrying electrons can be scattered or trapped in the electric wave field and a pseudo-resistivity can arise. To maintain the large scale current, a quasi-parallel electric field is set up to accelerate electrons and keep current continuity.

The theory of anomalous resistivity has been discussed earlier [*Kindel and Kennel,* 1971 and *Papadopoulous,* 1977] and also in association with waves in the auroral region at Venus [*Scarf* et al., 1985]. The resistivity due to ion acoustic waves is discussed in paper IV in this thesis.

9 Conclusions

Up until now we have discussed both different large-scale regions in our magnetosphere and small-scale wave-particle interactions. Even though their time and length scales vary a lot, they are still connected to each other. Small-scale processes are very important for larger scale processes. The energy source driving the large-scale processes in the nightside auroral region is primarily a generator in the magnetotail. During an expansion phase of a so-called magnetic storm, or sub-storm, a reconnection of magnetic field lines in the magnetotail can occur. Magnetic energy is then converted to particle kinetic energy and convected towards the Earth. This generator drives currents in flux tubes connected to the auroral ionosphere where energy is dissipated. On these field lines, electrons are accelerated by quasi-static parallel electric fields towards the Earth, but how these parallel electric fields can be maintained in collisonless plasma is not known. One theory is that the density is very low and therefore there are only a few charge carriers and for the large-scale current to be maintained between the generator and the ionosphere, a quasi-static parallel electric field must appear.

However, this may not be the only explanation for a quasi-static parallel electric field.

Broadband waves are the most common waves on these auroral magnetic field lines up to altitudes of at least 4-5 Earth radii. Waves in collisionless plasma are important because they can interact with particles and redistribute energy. In this thesis we have identified broadband waves on auroral magnetic field lines at altitudes around 4-5 Earth radii, which was thought to be above the region where the electrons get accelerated. We have identified the waves as consisting of a mixture mainly of electrostatic proton cyclotron waves and ion acoustic waves, i.e. waves on the same theoretical dispersion surface.

From observations we have found that ion acoustic waves can only be found in plasma where, at a first glance, there is no cold electron population. According to linear theory, the ion temperature has to be lower than the temperature of the electrons for ion acoustic instability to arise. However, these conditions were only found in small regions and are consistent with so-called inverted-V structures earlier observed at lower altitudes.

Mainly high-energy accelerated electrons and no cold electrons characterize an inverted-V structure. The name inverted-V comes from the shape of the electron energy vs. time spectrogram, which looks like a letter V upside-down.

In these upward current regions we have observed quasi-static parallel electric fields, which are well correlated with the ion acoustic waves. We believe that low energy electrons in the large scale current are scattered or trapped by the electric wave field and cause an anomalous resistivity. A parallel electric field has to be set up and accelerate electrons to maintain the large scale current. Subsequently generated parallel electric fields can accelerate electrons up to a few keV.

According to the theory that the electric ion acoustic wave-field can retard or trap electrons, there has to be a cold electron population (up to a couple eV) present because the potential in the wave is not large enough to affect the high-energy electrons. One explanation for why the ion acoustic instability can arise even though cold electrons are present is that the distribution of the cold population has no negative slope in the particle distribution function of energies corresponding to the phase velocity of the wave i.e., it is not a Maxwellian. However, the cold population is difficult to detect by the electron spectrometers onboard Cluster, which is why we cannot be sure about the shape of the distribution.

So, is the acceleration region stretched further along the magnetic field lines to higher altitudes than previous expected, or is this another, local acceleration mechanism? We don't know that, but for the first time, we have shown from direct observations that resistivity caused by particle-wave collisions in astroplasmas is important for particle acceleration.

9.1 And what's next?

We have found signatures of reconnection and sub-storm onsets associated with the observations of regions containing ion acoustic waves. It is known that sub-storms are related to the display of aurora. But how much importance have the ion acoustic waves in the large-scale phenomena? Can these regions containing ion acoustic waves be a "tracer" for reconnection in the tail?

In this thesis we have shown that small-scale processes indeed are important for the large-scale processes and a possible next step is to use conjunctions of the new Chinese/European mission called the Double Star Program and Cluster. During conjunction events, it is possible to get measurements of two key regions at the same time, the source and sink region. From such a study we can hopefully reveal ongoing energy processes along geomagnetic field lines connecting the magnetotail to the auroral ionosphere, i.e. the source to the sink.

10 Summary of papers

10.1 Paper I

Identification of Broadband Waves above the Auroral Acceleration Region: CLUSTER Observations

We investigate broadband emissions at frequencies above the ion gyrofrequency on auroral field lines at geocentric distances of about 4.5 Earth radii. Observations by the Cluster satellites are used to study the wave characteristics and to determine the wave modes involved.

All events include some bursts of broadband emissions with a substantial component of the electric field parallel to the geomagnetic field. Studying the polarization of the emissions we find that linear waves in homogeneous plasma can be used to theoretically describe the observations.

The broadband emissions include short bursts of ion acoustic waves, and longer periods of ion Bernstein and electrostatic ion cyclotron, waves. All waves occur during the same event within a few seconds, with EIC waves as the most common. Theoretically there is no sharp limit between these wave modes and they can be described by the same dispersion surface. These emissions are closely associated with low-frequency Alfvén waves, indicating a possible generation mechanism.

10.2 Paper II

Cluster Observations and Theoretical Explanations of Broadband Waves in the Auroral Region

In the second paper we continue the identification of the broadband waves, but in this paper we use two different methods to study the polarization of the waves at 10 to 180 Hz. We find that much of the wave emissions are consistent with linear waves in homogeneous plasma. Observed waves with large electric field perpendicular to the geomagnetic field are more common (electrostatic ion cyclotron waves), while ion acoustic waves with a large parallel electric field appear in smaller regions without cold (tens of eV) plasma. The regions void of cold plasma are interpreted as parallel potential drops of a few hundred volts.

10.3 Paper III

Interferometric Identification of Ion Acoustic Broadband Waves in the Auroral Region: CLUSTER Observations

In paper III we use a third method to identify the observed broadband waves and determine the phase velocity and **k** vector for parallel and oblique broadband waves. We use internal burst mode data from the EFW electric field and wave instrument onboard the Cluster spacecraft to retrieve phase differences between the four probes of the instrument. The retrieved characteristic phase velocity is of the order of the ion acoustic speed and larger than the thermal velocity of the protons. The typical wavelength obtained from interferometry is around the proton gyro radius and always larger than the Debye length. We find that in regions with essentially no cold electrons the observed broadband waves above the proton gyro frequency are consistent with upgoing ion acoustic and oblique ion acoustic waves.

10.5 Paper IV

Direct Observations of Electric Fields and Particle Acceleration Caused by Anomalous Wave-Particle Resistivity in Space Plasmas

Electrons hitting the upper atmosphere cause the aurora, visible to the naked eye. The electrons are accelerated by quasi-static electric fields parallel to the geomagnetic field. It is not known how such kilo-Volt potential differences can be maintained in collisionless plasmas. Similar acceleration processes are common in many astro-plasmas such as planetary magnetospheres, the solar corona and galactic surroundings. We present observations by two Cluster spacecraft of large-scale currents, resistivity caused by ion-acoustic waves, and the subsequently generated parallel electric fields of a few mV/m. Together with previous observations by all four Cluster satellites, this is consistent with an extension of the acceleration region along the geomagnetic field of a few thousand kilometres, resulting in the observed electron energy of a few keV. For the first time we can use direct observations to show that resistivity caused by particle-wave collisions in astroplasmas is important for particle acceleration.

10.5 Papers not included in thesis

Wahlund, J.E., Yilamaz, A., **Backrud, M.** et al., Observations of Auroral Broadband Emissions by CLUSTER. *Geophys. Res. Lett.*, 30, 1563 , 2003.

Stenberg, G., Oscarsson, T., André, M., **Backrud, M**. et al., Electron-scale structures indicating patchy reconnection at the magnetopause?, submitted to *Ann. Geophys.,* 2005.

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