The importance of waves in space plasmas
Examples from the auroral region and the magnetopause

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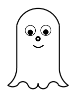
To my favorite supervisor, Dr. Tord Oscarsson,
for his friendship and for all the fun we had.



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Abstract. This thesis discusses the reasons for space exploration and space science. Space plasma physics is identified as an essential building block to understand the space environment and it is argued that observation and analysis of space plasma waves is an important approach.

Space plasma waves are the main actors in many important processes. So-called broadband waves are found responsible for much of the ion heating in the auroral region. We investigate the wave properties of broadband waves and show that they can be described as a mixture of electrostatic wave modes. In small regions void of cold electrons the broadband activity is found to be ion acoustic waves and these regions are also identified as acceleration regions. The identification of the wave modes includes reconstructions of the wave distribution function. The reconstruction technique allow us to determine the wave vector spectrum, which cannot be measured directly. The method is applied to other wave events and it is compared in some detail with a similar method.

Space plasma wave are also sensitive tools for investigations of both the fine-structure and the dynamics of space plasmas. Studies of whistler mode waves observed in the boundary layer on the magnetospheric side of the magnetopause reveal that the plasma is organized in tube-like structures moving with the plasma drift velocity. The perpendicular dimension of these tubes is of the order of the electron inertial length. We present evidence that each tube is linked to a reconnection site and argue that the high density of tube-like structures indicates patchy reconnection.

Keywords: Plasma waves, magnetospheric physics, magnetopause, auroral region, wave distribution function, space exploration, reconnection, current tubes.

Publications

This thesis is based on the following papers:

I Oscarsson T., **G. Stenberg**, and O. Santolík, Wave mode identification via wave distribution function analysis, *Physics and Chemistry of the Earth, 26*, 229–235, 2001.

II Stenberg, G., T. Oscarsson, M. André and C. C. Chaston, Investigating wave data from the FAST satellite by reconstructing the wave distribution function, *Journal of Geophysical Research, 107,* doi:10.1029/2001/2001JA900154, 2002.

III Backrud, M., **G. Stenberg**, M. André, M. Morooka, Y. Hobara, S. Joko, K. Rönnmark, N. Cornilleau-Wehrlin, A. Fazakerley and H. Rème, Cluster observations and theoretical explanations of broadband waves in the auroral region, submitted to *Annales Geophysicae*, January 2005.

IV Stenberg, G., T. Oscarsson, M. André, A. Vaivads, M. Morooka, N. Cornilleau-Wehrlin, A. Fazakerley, B. Lavraud and P. M. E. Décréau, Electron-scale sheets of whistlers close to the magnetopause, submitted to *Annales Geophysicae*, January 2005.

V Stenberg, G., T. Oscarsson, M. André, M. Backrud, Y. Khotyaintsev, A. Vaivads, F. Sahraoui, N. Cornilleau-Wehrlin, A. Fazakerley, R. Lundin and P. M. E. Décréau Electron-scale structures indicating patchy reconnection at the magnetopause?, submitted to *Annales Geophysicae*, April 2005.

Contents

Preface

Many thesis' introductions are written like textbooks, where the discussion on the relevance of the research field is reduced to a few vague sentences. This is unsatisfactory: Mature scientists should be able not only to explain their scientific fields but also to justify them in a broader perspective.

The purpose of this thesis is to discuss the reasons for the exploration of space in general, to justify the scientific field of space plasma physics, and to present arguments for focusing on observation and analysis of space plasma waves.

Gabriella Stenberg

1

Why on earth?

We choose to go to the moon in this decade
and do the other things,
not because they are easy,
but because they are hard...

John. F. Kennedy, 1962

On the 20th of July 1969 Neil Armstrong takes the first step on the dusty surface of the Moon: a moment that constitutes the highlight of the Apollo project. During a decade this giant space adventure has engaged more than 400 000 people and, up to 1973, the total funding sums up to almost 20 000 000 000 USD [Cortright, 1975; Orloff, 2001]. The landing on the Moon is regarded as one of the milestones in human history, but is not a result of a sincere desire to explore the universe. Instead, it is accomplished as a strategic move in the Cold War, primarily reflecting the need of the United States to retain control of the power balance. The ongoing space race is a political contest, a continuous summit meeting using a different arena [Gatland, 1985].

Still, to consider the exploration of space as merely a political issue is fundamentally wrong. It is reducing man to a creature interested in power and money only; denying the inherent curiosity as one of our racial characteristics. We are born to discover, investigate and analyze. Our ability to survive is based on a flexibility resulting from a combination of inventiveness and constantly increasing knowledge. The essence of humanity is expressed through questions both existential and scientifically relevant: From where do we originate? How did it all begin? How will it end? Are we alone in the universe?

When the first man-made satellite is launched in 1957 no one imagines the consequences of the rapid development that follows; half a century later space technology is an integrated part of the society. Worldwide communication and navigation depend on space applications, satellite images are compulsory elements of every weather report and our every-day lives are filled with things no longer recognizable as spinoffs from space technology. Sunglasses, athletic footwear, smoke detectors, quartz watches and bar codes are among 30 000 other commercial products having entered the consumer market since the beginning of the Space Age. Space technology has also helped to improve both diagnosis and treatment of different deceases, including cancer [NASA, 2004].

Yet, most important from a future perspective are the insights gained when viewing the Earth from space. The fragility of the planet is obvious when observed from a distance; the reckless hunt for the limited resources leaves visible scars, air and water pollution appear as planetary bruises, and the atmosphere with the life-supporting ozone layer is just a very thin transparent skin covering the surface. In a sense, the step out into space may also be a step towards a human maturity, where exploitation is replaced by management. Today, satellite technology is regarded as an indispensable tool in environmental research and surveillance [e.g. United Nations, 2002]. It is an absolute necessity to meet the big challenges of our time: to monitor and slow down the global warming and to achieve a sustainable development.

The planning of new huge space projects promises further progress, although we cannot today predict the outcome. Hence, whether or not the 700 000 000 SEK yearly invested by the Swedish National Space Board on space related activities [Rymdstyrelsen, 2005] are better spent on health care, road maintenance, or agricultural subsidies should not be evaluated looking only at the immediate benefits. Likewise, a manned mission to Mars conducted by NASA or ESA is not justified by purely scientific reasons, but is an invitation to once again share the excitement of discovering the unknown. The idea itself is a request to fasten the seatbelts and join an unforgettable expedition. A continuing space exploration is not only inevitable but also an essential and inspiring ingredient of a developing civilization.

2

The plasma universe

In science the credit goes to the man
who convinces the world,
not the man to whom the idea first occurs.

Sir Francis Darwin, 1914

SCIENCE MAY NOT be the only reason or not even the conclusive argument for space missions. Yet, regardless of the underlying motives the scientific outcome is still considerable. Scientists are attracted to the new hunting-grounds full of unsolved problems and irresistible challenges. They share the desire to reach the bounds of the observable universe; to reveal the beginning of time itself. They seek the principles ruling the universe to explain the presence of ourselves [Burbidge, 1983].

Space science is needed to answer the thrilling questions about the origin of the solar system and to guide in the search for extraterrestrial life. Space science is also needed in order to use space to improve and protect life on Earth. Knowledge of the space environment enable us to construct spacecraft surviving the tough conditions in orbit. In recent years we have also learnt that space processes may affect the Earth directly and on shorter times scales than expected. Climate changes and even smaller variations in the weather are suggested to be linked to the solar activity and the solar-terrestrial interaction [Svensmark, 1998, 2000; Marsh and Svensmark, 2000].

Space science is truly multi-disciplinary. Astronomy, astrophysics, ionospheric chemistry, planetology, space plasma physics and exobiology are all just examples of branches within this vast field. With different objectives, approaches and methods they complement each other, and future break-throughs will probably require interdisciplinary initiatives [Roederer, 1988].

Overwhelmed by excitement, realizing simultaneously the beauty and the complexity of the field of space science, we run the risk of splitting our resources in an attempt to attack all the problems at once. However, the definition of science urges us to consider a more professional attitude: According to the encyclopedia science means acquiring knowledge in a systematic and methodical way [Frängsmyr, 2005]. To accomplish the efficiency suggested by such an rational approach it is of vital importance that we focus on the relevant issues. Neither our strength and ability nor our budget is unlimited and to secure further achievements we must identify and concentrate on the essential topics.

It is easy to point out space plasma physics as one of these fundamental building blocks, necessary to understand both the near-earth space environment and the universe as a whole. More than 99% of the visible matter in the universe is assumed to be in the plasma state, sometimes referred to as the fourth state of matter [Chen, 1984].

A plasma can be thought of as a gas of electrically charged particles. Hence, in systems involving plasmas not only gravitational forces but also electromagnetic forces become important and, in fact, they govern much of the dynamics. Even in essentially collisionless environments the particles have an influence on each other. To predict the behavior of a system including an uncountable number of particles interacting over large distances seems almost impossible. Fortunately, the near-neighbour forces can be neglected. The electric field introduced by an individual particle is shielded out by the presence of the nearby particles. Thus, on scales larger than the shielding distance, collective effects dominate and the individual particles need not be considered [e.g. Chen, 1984; Krall and Trivelpiece, 1986].

It is time to realize that we live in a plasma universe and that this may have wider implications than we imagine today. Viewed through the plasma spectacles the universe presents itself rather differently and its secrets may be unlocked [e.g. Alfvén, 1971, 1986, 1987]. One of the keys to the plasma universe is space plasma waves. As carriers of energy and information they are responsible for much of the action in space plasmas.

3

The nature of space plasma waves

Det finns ting bara experter
inte kan förstå[1]

Rolf Edberg, rsbarn med Pleiaderna, 1987

SPACE PLASMAS are immensely rich in wave phenomena. Fascinating new possibilities arise as electromagnetic oscillations couple to the motion of the charged particles and a plasma presents the most imaginative combinations of electromagnetic and acoustic waves.

Even if we restrict ourselves to linear waves in homogeneous plasmas we face a exceptional complexity and we encounter wave properties very different from what we are used to. For ordinary light, the angular frequency is given by $\omega = ck$, where k is the length of the wave vector and c is the speed of light. The angular frequency ω is related to the frequency, f, through $\omega = 2\pi f$ and $k = 2\pi/\lambda$, where λ is the wavelength. In a plasma ω is generally no longer a linear but a more complicated function of k [Chen, 1984; Krall and Trivelpiece, 1986].

The presence of an external magnetic field (e.g. the geomagnetic field) introduces further delicacy. A charged particle moves easily along such a field, while the gyration of the particle around the field lines restrains the motion in the perpendicular direction. Hence, a plasma behaves very differently in these two directions. As a consequence the propagation properties of a plasma wave depend on the angle between its direction of propagation and the external field, and the angular frequency is a function of both $k_\perp$ and $k_\parallel$. Here, $k_\perp$ and $k_\parallel$ are the components of the wave vector perpendicular and parallel to the external magnetic field.

The general dispersion relation, $\omega = \omega(k_\perp, k_\parallel)$, then describes a surface in $(k_\perp,\ k_\parallel)$-space. Such dispersion surfaces [André, 1985] constitute an elegant way of viewing plasma waves. Each point on the surface represents a wave at a certain frequency, with a certain

[1] Author's translation: There are things only experts cannot understand.

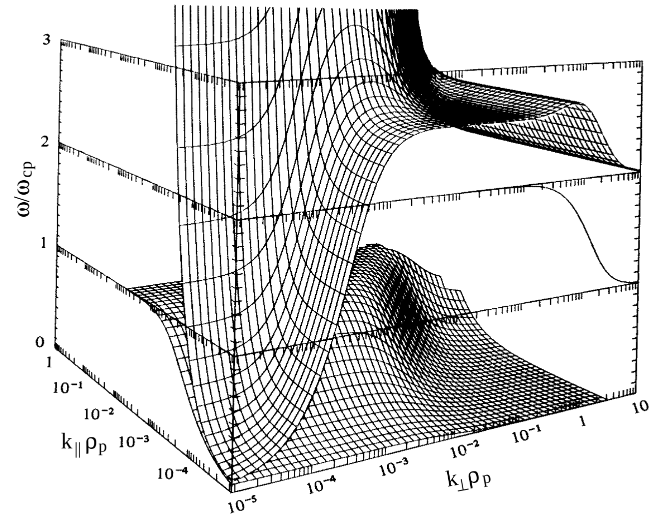

FIGURE 3.1 Dispersion surfaces describing the low frequency waves present in a plasma with only protons and electrons. The plasma density is 1.6 cm^{-3}, the magnetic field is 7000 nT and he particle temperatures are 2 eV (23 000 K). The frequency is normalized to $\omega_{cp} = 2\pi f_{cp}$, where f_{cp} is the proton gyrofrequency. The parallel and perpendicular wave vector components are normalized to the inverse of the proton gyroradius $1/\rho_p$. From André [1985].

wavelength and propagation direction, and the entire surface may be referred to as a wave mode. Figure 3.1 shows two of the wave modes supported by a proton-electron plasma. The frequency is normalized to $\omega_{cp} = 2\pi f_{cp}$, where f_{cp} is the proton gyrofrequency. The parallel and perpendicular wave vector components are normalized to the inverse of the proton gyroradius $1/\rho_p$. It is apparent from Figure 3.1 that the wave frequency is generally a complicated function of the two wave vector components. We also note that at a given frequency there are many possible wave vectors, and for a given wave vector there may be more than one possible frequency.

Space plasmas consist of particles with very different masses. The large mass ratio between protons and electrons creates the possibility for oscillations to occur both on the time scales of the protons and on electron time scales. Figure 3.1 displays two of the wave modes associated with the proton time scales. There are additional modes at higher frequencies related to the electron time scales. A plasma consisting of additional particle species, e.g. O^+ or He^+, can support even more wave modes.

The wave properties do not only change between the wave modes. Usually the wave characteristics vary much between different parts of the same surface, e.g. the gradient at each point is proportional to the group velocity. The polarization of the wave, that is, the phase and amplitude relations between the wave field components, also changes across a surface. Detailed discussions about waves in plasmas can be found in, for example, Chen [1984], Krall and Trivelpiece [1986] or Kivelson and Russell [1995]. A comprehensive summary, including an introduction to observations and analysis of space plasma waves is provided by Stenberg [2002].

Within linear theory the plasma waves do not affect the plasma supporting them. This is an approximation that work surprisingly well in many cases. As the wave properties reflect the nature of the plasma in which they propagate as well as the characteristics of the plasma responsible for the wave generation, space plasma waves constitute a sensitive tool for investigations of both the fine-structure and the dynamics of space plasmas.

However, the growth or the damping of plasma waves produces changes of the particle distributions [Krall and Trivelpiece, 1986] that need nonlinear treatments. Such wave-particles interactions enable the transfer of energy between different plasma populations and explains why waves play decisive roles in a variety of important processes in space.

4

The importance of waves in space plasmas

Everything of importance has been said before
by somebody who did not discover it.

Alfred North Whitehead (1861–1947)

IT IS WITH wonder and genuine surprise the space science pioneers interpret their rocket and satellite observations. Instead of encoun-

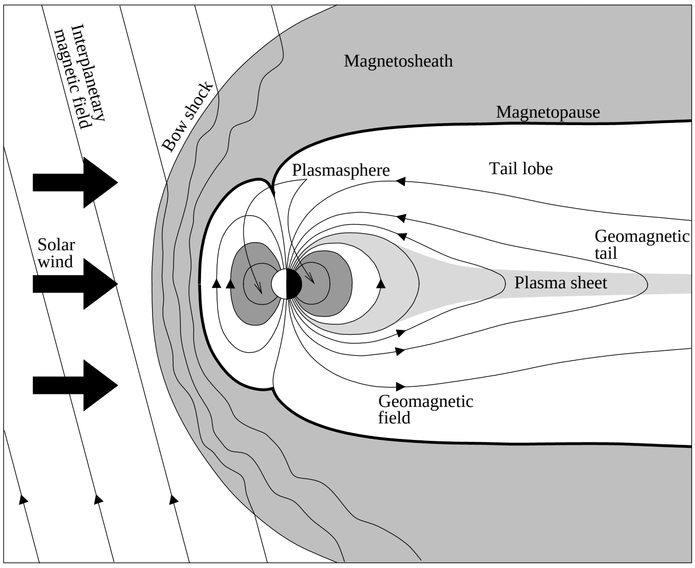

FIGURE 4.1 The solar wind (plasma streaming outwards from the sun) interacts with the Earth's magnetic field and forms the magnetosphere. From Hamrin [2002].

tering a structureless vacuum they reveal a highly organized plasma environment [Fälthammar, 1992]. The near-earth space is composed of a large number of regions with very different properties separated by incredibly thin boundaries. In addition, it is discovered that due to interaction with plasma streaming from the sun (the solar wind) the magnetic field of the Earth is deformed and confined to a cavity. The existence of such a cavity is suggested already by Chapman and Ferraro [1930] and today we refer to it as the magnetosphere. Figure 4.1 shows a modern illustration of this fundamental concept.

Waves as main actors

Already one of the very first space-born instruments enabled the discovery of the so-called radiation belts [Van Allen and Frank, 1959]. These regions are characterized by high-energy particles, which are

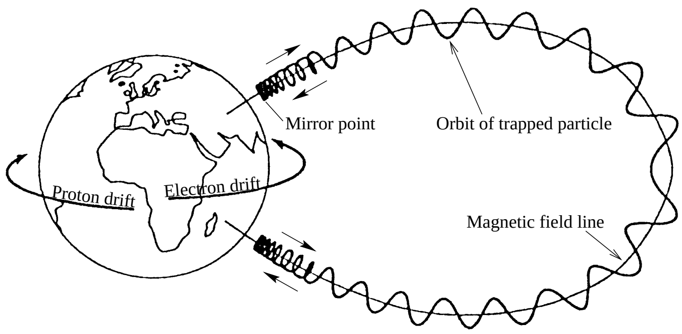

FIGURE 4.2 High-energy particles trapped in the magnetic field constitute the radiation belts. A typical particle orbit is shown. The particle gyrate, bounce and drift around the Earth simultaneously. From Fälthammar [1992].

trapped in the magnetic field and bounce back and forth between the magnetic poles, before they are eventually lost in the atmosphere. The situation is depicted in Figure 4.2.

The high energy content in the radiation belts comprises a threat to both satellite electronics and astronauts. Hence, all space missions strive to make the passage(s) through the radiation belts as short as possible to minimize the risk of damages. A solid understanding of radiation belt dynamics is important to avoid this unfortunate obstacle to spaceflight.

Space plasma waves are essential as they regulate the flux of particles in the radiation belts. A converging magnetic field acts as a mirror. As a particle moves towards one of the poles, the increase in magnetic field strength causes the pitch angle to increase. The pitch angle is the angle between the particle's velocity vector and the magnetic field. At a certain altitude the velocity becomes perpendicular to the magnetic field and the mirror force makes the particle move up along the field line again. At any given position along the particle's orbit, it is the local magnetic field strength together with the pitch angle that determines whether the particle will enter the atmosphere or bounce. A smaller pitch angle places the mirror point at lower altitudes. Hence, if the angle is small enough the particles do not mirror at all but collide with atmospheric particles. This loss of particles creates an unstable particle distribution, which is responsible for the generation of waves. The generated waves are able to change the pitch angle of the particles in a process known as pitch angle diffusion. Hence, new particles are lost in the atmosphere and new waves are generated. This self-regulating process would slowly empty the radiation belts if they were not continuously refilled [Kennel and Petschek, 1966; Lyons et al., 1971, 1972].

It may seem as a great step, but from a wave point of view the distance from the radiation belts to the question of life on Mars is not very long. Lately much attention is drawn to the exploration of the Red Planet: Could Mars have been a habitable place in the early days of the solar system? The intriguing question is strongly linked to a presumed presence of an atmosphere and perhaps also a global ocean on a younger planet. There is evidence of long-ago water on the surface and even today the erosion of a very thin atmosphere is observed. The interpretation of the results and their implication is still under discussion [e.g. Lundin et al., 2004; Kerr, 2005]. However, similar erosive processes take place in the Earth's magnetosphere. Oxygen ions originating from the atmosphere are found in the upper parts of the magnetosphere. Hamrin et al. [2002] show that so-called broadband waves are responsible for a perpendicular heating of the ions. The mirror force then causes the particles to move towards a weaker magnetic field and their large perpendicular velocity turns into a large parallel velocity. Hence, the physics leading to the escape of ions is, in part, the same physics regulating the radiation belt particles. The erosion of the atmosphere is not as violent as on Mars since the magnetosphere acts as a deflection shield against the solar wind. The outflow of oxygen ions is up to a few kilograms per second, which does not noticeably affect the atmosphere even on geological time scales [André and Yau, 1997; Yau and André, 1997]. Detailed knowledge of the energization and the subsequent outflow of ions is nevertheless of large interest in order to analyze where and how conditions suitable for life arise.

Atmospheric outflow and the regulation of the fluxes in the radiation belts are two of many examples of processes where space plasma waves play the principal part. They prove that observation and analysis of waves are of importance to both the commercial space industry and the scientific community. Wave-particle interaction is a key element and to gain further insights in the presented as well as other processes, a focus on space plasma waves is absolutely necessary.

In both the topics briefly discussed above, knowledge of the wave vectors is of fundamental interest. However, wave vectors are very difficult to measure directly. Moreover, in the general case we are not observing a single plane wave with a fixed wave vector (that is, a single point on a dispersion surface), but the wave energy is spread in wave vector space. In **Paper I** and **Paper II** a method to reconstruct the spectrum of wave vectors from satellite observations is evaluated and established as a useful tool. In **Paper III**, we are able to explain observations of broadband waves in terms of linear wave modes using this method. Thereby, through careful wave analysis, our understanding of the plasma universe is slowly increasing.

Waves as catalysts

Striking auroras, magnetic storms and all other action within the Earth's magnetosphere depend ultimately on the entrance of plasma and energy from the solar wind. A process referred to as magnetic reconnection is assumed to enable the intrusion. Reconnection occurs along the boundary between the solar wind and the magnetosphere, where the interplanetary magnetic field in the solar wind connects to magnetospheric field lines. The idea is illustrated in Figure 4.3, which also depicts how magnetic field energy is converted into kinetic energy of electrons and ions [Paschmann et al., 1979]. Observations of the resulting particle jets are a strong support for this picture [Phan et al., 2000]. A second place where reconnection occurs is in the magnetotail, where the reconnection recreates closed magnetospheric field lines [Kivelson and Russell, 1995].

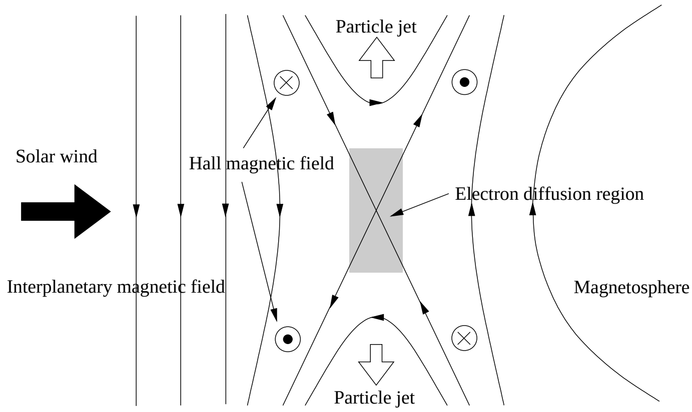

FIGURE 4.3 The geometry of a reconnection site at the magnetopause. The interplanetary magnetic field connects to the magnetic field of the magnetosphere. Particles and energy can then be transfered between the two regions.

When the electric conductivity is high the plasma and the external magnetic field are tied to each other. The magnetic field lines move together with the plasma as if they were frozen into it. This frozen-in condition is responsible for the organization of the magnetospheric plasma in different regions separated by thin boundaries. To allow reconnection the frozen-in condition must break down at least in a small so-called diffusion region. In the collisionless space plasma one way to achieve this breakdown is through anomalous resistivity or viscosity, that is, artificial collisions, caused by waves [Treumann, 2001]. In this case the waves play a less prominent part, but their presence may still be required for a dramatic energy transfer to take place. The catalytic function of space plasma waves should not be underestimated; information on what is triggering a fundamental process is invaluable.

Anomalous resistivity is also suggested to provide means to generate the electric fields parallel to the geomagnetic field associated with the aurora [Lysak, 1990]. Such parallel fields accelerate electrons towards the Earth. As the electrons collide with the upper atmosphere their kinetic energy is transformed into visible light. Based on the results obtained in **Paper III**, Backrud [2005] discovered that ion acoustic waves can cause the resistivity, which together with the field-aligned current, is needed to generate the parallel electric fields observed.

Waves as diagnostic tools

Space plasma waves are not only of importance when they trigger or govern processes of major interest. They are also an enormous asset in monitoring events at a distance and as sensors of the plasma composition and structure. The plasma characteristics reveal themselves as fingerprints in the wave emissions. The eigenfrequency of a plasma, the electron plasma frequency, ω_{pe}, is proportional to the square root of the density, and an observation of ω_{pe} is in many cases the most reliable estimate of the density. Other naturally occurring frequencies aid in determining, for example, the ion composition [e.g. Oscarsson et al., 1997].

Waves may also carry messages from far away. The heliopause is the boundary where the solar wind meets the interstellar medium. A teardrop-shaped surface, marking the edge of the heliosphere, is expected to form as the sun moves with respect to the interstellar medium. A standing shock (the termination shock), where the su-

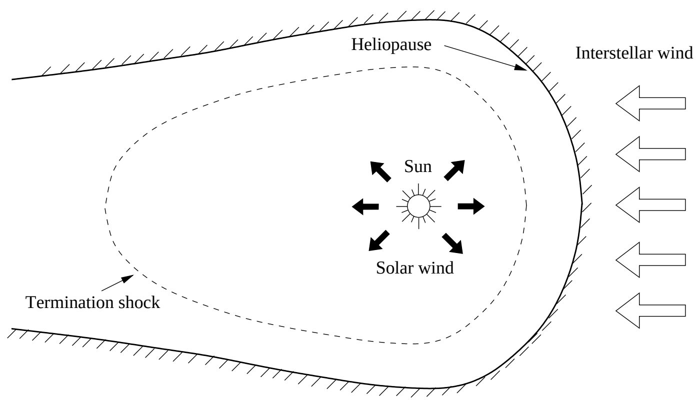

FIGURE 4.4 The boundary where the solar wind encounters the interstellar medium is called the heliopause. A standing shock, where the supersonic solar wind abruptly slows down, is formed inside the heliopause.

personic solar wind abruptly slows down, is assumed to be located well inside of the heliopause [Gurnett et al., 1993]. The situation is illustrated in Figure 4.4.

Voyager 1, the most distant human-made object in the universe, still returns unique scientific data. Launched in the summer of 1977 the spacecraft untiringly continues its journey, approaching the amazing distance of 100 astronomical units (AU), yet without encountering the heliopause. However, already in 1984, signals from this outer frontier of the solar system were captured. The radio wave emissions at 2–3 kHz detected by the plasma wave receivers at both Voyager 1 and Voyager 2 were interpreted as the first remote observations of the heliopause [Kurth et al., 1984]. Similar wave emissions made it possible for Gurnett et al. [1993, 2003] to estimate the distance to the frontier comprising the outermost plasma boundary of the solar system. According to those calculations the heliopause is located about 150 AU away. In recent years observations of increased energetic particle activity indicates that the spacecraft are approaching the termination shock [McDonald et al., 2003]; some argue that Voyager 1 may already have entered the shock [Showstack, 2003].

Wave observations made remote-sensing of the heliopause possible before other means of investigation were available. They enable estimations of the plasma density and composition through detection of characteristic frequencies. Finally, wave observations are able to resolve fine-structures in the plasma that cannot be detected by other instruments.

ESAs four-spacecraft mission Cluster [Escoubet et al., 1997, 2001] is focused on small-scale plasma structures. In **Paper IV** and **Paper V** the study of whistler mode emissions observed by Cluster close to the magnetopause reveals unexpected fine-structure. We find that the boundary layer on the magnetospheric side of the magnetopause is characterized by small magnetic field-aligned tube-like current structures generating whistler waves. The current structures we resolve are so small perpendicular to the magnetic field that they are unable to detect with, for example, particle instruments. We argue that these tubes are coupled to a reconnection diffusion region, and, hence, information on the reconnection structure is mediated by the waves.

Very thin layers with currents and strong electric fields are also observed at the magnetopause. They are investigated by André et al. [2004] and Vaivads et al. [2004] and are assumed to be associated with the reconnection process.

5

Facing the future

It is difficult to say what is impossible,
for the dream of yesterday is the hope of today
and the reality of tomorrow.

Robert H. Goddard (1882–1945)

THE FINAL destiny of humanity will not be decided on the surface of the Earth only. Our step into space is irreversible: a door to the future impossible to close. Out there lies the hope of discovering the origins of our race. Out there lies the hope of acquiring both wisdom and knowledge enough to protect and save our planet. The vast unknown is quietly awaiting the brave explorers and those willing to investigate, interpret and explain its mysteries.

The recognition of a plasma universe is necessary in order to understand both the near-earth environment and the outermost borderlands of the universe. To realize that the dynamics to a large extent is governed by plasma processes may both fascinate and puzzle. Observation and analysis of space plasma waves is a way to turn confusion into comprehension. Like the circulatory system of our bodies, space plasma waves constitute the transportation system for energy and information in the plasma universe. They play the principal part in several identified key processes. They serve as catalysts, triggering dramatic events, and they are invaluable as diagnostic tools.

To ensure future progress in space physics virtually all scientific space mission payloads should include plasma wave instruments. Observation techniques and analysis methods have to be constantly improved. Space plasma wave experts must not isolate themselves, but take their responsibility in joint projects, within the field of space physics as well as in more interdisciplinary contexts. Finally, wise leadership together with a well-organized coordination of large, international and multi-scientific projects is a (sometimes underestimated) key to scientific success.

The universe is encouraging us to reveal its secrets. It is up to us to decide whether or not to accept the challenge.

6

Summary of papers

Houston, we've had a problem.

J. Swigert on Apollo 13, 1970

Paper I

Wave mode identification via wave distribution function analysis

The first paper is aimed at evaluating how wave distribution function analysis can be used for identifying wave modes in a case where two wave modes overlap. A second objective is to compare the results from two independently developed methods for reconstructing the wave distribution function. For this purpose we analyze waves close to the proton gyrofrequency recorded by the Freja satellite at 1700 km altitude in October 1993.

The two reconstruction methods yield similar but not identical results. They both show that a mixture of right-hand and left-hand polarized waves are present. However, there are indications that below the so-called cross-over frequency only the left-hand mode contributes significantly to the wave energy.

The two reconstruction methods are different as far as the regularization procedures are concerned, but the differences in the results cannot be directly related to differences in the methods. Rather, the variations between the methods can be seen as a measure of the uncertainty of the reconstructed wave energy distributions.

Paper II

Investigating wave data from the FAST satellite by reconstructing the wave distribution function

In paper II we apply the wave distribution function analysis technique to a wave event observed by the FAST satellite at 4000 km altitude above the southern auroral oval. The power spectra of the electric and magnetic fields reveal wave emissions at the local proton gyrofrequency and at its first four harmonics.

To investigate the wave mode structure we use a five-component plasma model. Our analysis shows that the downgoing electrons are responsible for the wave growth at the gyrofrequency. The results from the reconstruction of the wave distribution function are in good agreement with the predicted instability.

The reconstruction gives a very clear angular distribution of the wave energy, which can be explained by a simple geometric picture. We assume that the FAST satellite is passing through the outer edge of an auroral arc in which the waves are generated. It is then natural that the wave energy mainly originates from the direction along the arc seen from the satellite. The waves traveling in this direction will have the most time to grow as they are inside the region with precipitating electrons for the longest time.

Paper III

Cluster observations and theoretical explanations of broadband waves in the auroral region

Broadband waves observed in the auroral region are a source of discussion. They are known to be important for ion heating, but the wave modes involved and the generation mechanisms are still under debate. In paper III we investigate broadband emissions recorded by the Cluster spacecraft at 4 R_E in the nightside auroral region. We show that the observations can be interpreted within the framework of linear waves in a homogeneous plasma.

We conclude that the broadband activity is a mixture of essentially electrostatic modes, which all correspond to different parts of the same dispersion surface. Much of the broadband activity is electrostatic ion cyclotron waves, whereas ion acoustic and oblique ion acoustic waves are concentrated to small regions where no damping in the form of cold electrons are present. The regions void of plasma are interpreted as acceleration regions, which have not been reported at this high altitude before.

Paper IV

Electron-scale sheets of whistlers close to the magnetopause

The last two papers are concerned with the intriguing physics close to the magnetopause. The four Cluster spacecraft are designed to investigate such complex boundaries. In paper IV we use Cluster data to discover that whistler mode waves observed in the boundary layer on the magnetospheric side of the magnetopause are generated in thin sheets. The sheets appear to drift with the plasma velocity and the width of a sheet is less than an ion inertial length.

Electron data show that hot magnetospheric electrons disappear at the time when the waves are observed, which contributes to the wave growth. We suggest that this feature in the electron data indicate that the whistler-generating sheets are observed on field lines directly connected to a reconnection diffusion region.

This paper also shows that waves are a sensible tool to investigate structures finer than can be resolved with the particle instruments.

Paper V

Electron-scale structures indicating patchy reconnection at the magnetopause?

In the last paper we reveal that the whistler wave-generating regions are even smaller than estimated in paper IV. As the waves reflect the structure of the background plasma, we conclude that the low-latitude boundary layer plasma is organized in tube-like structures, with perpendicular dimensions on the order of the electron inertial length (c/ω_{pe}).

There seems to be a high density of whistler-generating tube-like structures and we argue that the region with tubes extends several Earth radii along the magnetopause. If all whistler-generation regions recorded couple to a reconnection site as is suggested in paper IV, the structure observed in the boundary layer may indicate an intermittent or patchy reconnection.

Acknowledgements

All we have to decide is what to do
with the time that is given us.

Gandalf in J.R.R. Tolkien's The Fellowship of the Ring

It might not have been very imaginative or very wise, but this thesis is nevertheless what I did with the time that was given me. And looking around, I realize to my surprise that this project also involved a substantial amount of other people. To all of them I am for ever in debt.

First of all, I turn to my supervisor Dr. Tord Oscarsson using the words of Frodo: "I am glad you are here with me. Here at the end of all things". Although our task was not as overwhelming as the one faced by Frodo and Sam, we would probably have given up if we had known from the beginning just how long and demanding the road would be. I am grateful that Tord had the courage, the will and the power to complete the mission. I appreciate his flexibility, his ability to listen unprejudiced to new arguments and his sense of humor. I sincerely enjoyed all the debates and constructive discussions we had and I am convinced that the time of close cooperation irreversibly changed us both for the better!

Just as Frodo and Sam sometimes needed help, this mission would not have been successful if the white wizard, Prof. Mats André, had not interfered at times. Just like Gandalf he seems to have an overview of the recent developments, several alternative routes from everywhere and a special liking for mysterious statements. If Mats should wear a pointed hat, nobody would probably see the difference between him and Gandalf.

My (sometimes very long!) working-days have been endurable due to a number nice hobbits with more or less odd personalities. There are, among others, my assistant supervisor Prof. Kjell Rönnmark, an inexhaustible source of knowledge, even more inscrutable than Mats André; my room-mate Joachim Wabnig, a quantum physics-lover with a Schwarzenegger-accent; the always-worrying Maria Hamrin, together with whom I intend to build the new Swedish space empire; the always-talking Patrik Norqvist, a sports freak and Springsteen-fan with literary ambitions; the hypochondriac perfectionist Hans Forsman, an affectionate runner; my favorite administrator Ann-Charlott Dalberg, an even more affectionate runner; and the good-natured nightshift personnel, Krister Wiklund and Michael Bradley.

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