Particle Acceleration and Wave Phenomena in the Auroral Region

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Abstract. Acceleration of charged particles, and emissions of electromagnetic waves over a wide range of frequencies, occur in the auroral region of the terrestrial magnetosphere. Many interesting results concerning such phenomena were presented at the second EGS Alfvén conference held in Stockholm during May 1999. We present a summary of some of these results. Our presentation includes recent investigations of the mechanisms accelerating electrons both upward and downward along the geomagnetic field in the auroral region, and of the waves causing energization and upward outflow of ionospheric ions. Wave phenomena such as Auroral Kilometric Radiation and various types of Solitary Waves are also discussed. © 2001 Elsevier Science Ltd. All rights reserved

1 Introduction

The auroral region of the terrestrial magnetosphere is a fascinating part of space, and also a part that can be investigated in some detail with satellites, sounding rockets and ground-based instruments. The second EGS Alfvén conference held in Stockholm May 3–7 1999 was devoted to auroral particle acceleration and related topics. This meeting produced a variety of interesting new results on the plasma physics and the electrodynamics, and on the particle acceleration and wave excitation processes, that take place in the auroral region. In the following we present a summary of some of the results discussed at the meeting. We do not attempt to cover all presentations, but rather try to give an overview of some of the major topics discussed during the meeting. Since several hundred scientific papers have been published on these topics during the last few years, we usually include references only to papers in these proceedings of the conference, and to a few other closely related articles.

The first part of the summary concentrates on the macroscopic aspects of the auroral current system. There is little doubt that the flow of currents along the geomagnetic field is an essential feature of the auroral region, and that these currents provide the energy source for the particle acceleration that occurs in this region. The discussion of these aspects can be conveniently divided into the three important regions that comprise the auroral circuit: the generator region, the auroral acceleration region, and the ionosphere. It is clear that the downward acceleration toward the Earth of auroral electrons to keV energies occurs at altitudes of a few thousand kilometers. It is also becoming evident that the density in the acceleration region can be very low. Several models of the acceleration of auroral electrons were discussed at the meeting.

After a summary of some macroscopic aspects we discuss microscopic processes, such as electromagnetic waves closely related to auroral particle acceleration. Auroral kilometric radiation are radio emissions emitted from inside the auroral acceleration region. Also, it is well known that ionospheric ions can be energized and subsequently escape from low altitudes into the outer magnetosphere. We summarize some recent observations and theories concerning the waves causing this ion outflow. Furthermore, recent high resolution field measurements indicate that many time varying fields occur as localized solitary waves rather than incoherent wave fields that fill large volumes of space. We present a brief summary of recent observations of solitary waves, and compare measurements from various satellites in different regions of the magnetosphere.
Auroral plasma physics should not be regarded as an isolated subject. Some relevant laboratory experiments are briefly mentioned throughout our summary. Also, auroral phenomena must be compared with processes in other parts of the magnetosphere, and ultimately with processes in other magnetospheres, including astrophysical plasmas.

2 The Generator Region

In some ways, the generator region of auroral field-aligned currents is the least understood aspect of the auroral current system. Most discussions of current generation focus on the physics in the outer magnetospheric regions, such as the low latitude boundary layer, the inner edge of the plasma sheet, or the plasma sheet boundary layer, that provide the generator for field-aligned currents. The traditional view holds that the field-aligned current generated in the magnetosphere can be determined by the divergence of the perpendicular currents caused by pressure gradients, \( \nabla \cdot \mathbf{B}_p \) or curvature drifts, or polarization drifts in the magnetosphere, leading to the so-called Vasyliunas equation (Vasyliunas, 1984):

\[
\mathbf{B} \cdot \nabla \left( \frac{j_\parallel}{B} \right) = -\nabla \cdot \mathbf{j}_\perp = \nabla \cdot \left( \frac{\mathbf{B}}{B^2} \times \left( \nabla p_\perp + (p_\perp - p_\parallel) \mathbf{B} \cdot \nabla \mathbf{B} + p \frac{d \mathbf{u}}{dt} \right) \right) \tag{1}
\]

This equation, however, has some faults as a governing equation for field-aligned current generation (Song, 1998; Song and Lysak, 1999; 2000). First of all, it does not include the full dynamics of the system. This equation is usually applied by considering a fixed pressure distribution and/or flow pattern, and the field-aligned current is calculated from these distributions. This procedure must be combined with dynamical equations for the pressure and flow in order to provide a complete theory of current generation. In addition, integration of this equation only gives the difference between the field-aligned current in the two ionospheres, or equivalently, the sum of the current flowing into each ionosphere. This is certainly important information; however, equation (1) does not determine how the field-aligned current is distributed between the two conjugate ionospheres. It is usually assumed that equal amounts of field-aligned current go into each hemisphere, but recent observations of the non-conjugacy of auroral arcs (Stenbaek-Nielsen and Otto, 1997; Sato et al., 1998) indicate that this is not necessarily the case.

From the point of view of an auroral physicist, the difficulty with this equation is that it does not consider the entire current system, i.e., the auroral acceleration region and the ionosphere are considered unimportant. An attempt to include such factors was discussed previously by Lotko et al. (1987), who developed a boundary layer model including the coupling to the ionosphere and the acceleration region. The reaction of the rest of the current system was also essential to the so-called tau-generator model of Vogt et al. (1999), which deals with the reflection of Alfvén waves in the generator region. An alternative point of view has been proposed by the Dartmouth and Alberta groups (Streltsov and Lotko, 1995; Samson et al., 1996a; Rankin and Tikhonchuk, 2000) who associate auroral arcs with the excitation of field line resonances. Such resonances can be excited either by ballooning instabilities (Samson et al., 1996b) or by the mode conversion of compressional waves at the resonant point (e.g., Samson et al., 1992).

Many issues remain to develop a complete theory of current generation. The detailed structure of the generator and how it arises in response to the dynamics of the rest of the magnetosphere remains as future work. Dynamic current generation occurs in the cusp and in the dayside magnetopause as well as in the magnetotail, and the relation of the dynamics in these regions to current generation and the relationship between the large-scale currents and smaller scale filaments remains to be worked out. Finally, an important question is how the generation of auroral currents and the development of parallel electric fields affect the dynamics of the outer magnetosphere itself. Some preliminary considerations on this subject are given by Haerendel (1992; 2000), Lysak and Song (1998) and by Blixt and Vogt (2000).

3 The Acceleration Region

A great deal of discussion of the acceleration region was presented at the second Alfvén conference, thanks to new detailed observations of the plasma in this region by satellites such as Freja and FAST. In addition, the observations from these lower-altitude satellites have shown conclusively that auroral particle acceleration is not confined only to the upward current region, which is associated with the bright aurora. There is also clear evidence that diverging electric fields in the downward current region are causing upward acceleration of electrons, sometimes to keV energies (Marklund et al., 1997; Carlson et al., 1998; Ergun et al., 1998a). Despite decades of theoretical speculation, there is still not a definitive theory of the microphysics of the acceleration region,
nor on the relation between this microphysics and the larger scale dynamics of the auroral currents. Nevertheless, this meeting engendered a great deal of discussion on the possibilities.

One aspect that seems clear at this point is that the auroral acceleration region has a very low density, and this low density plays an important role in the development of parallel electric fields. For example, the effect of electron inertia depends on the quantity $k_{\perp}^2 \lambda_e^2$, where $k_{\perp}$ is the wavevector perpendicular to the geomagnetic field, and $\lambda_e$ is the electron inertial length, $c/\omega_{pe}$. If it is assumed that the perpendicular wavelength scales as the distance between magnetic field lines, then $k_{\perp}^2 \lambda_e^2$ scales as $B_0/n$. Here $B_0$ and $n$ are the background magnetic field strength and density, respectively. A similar scaling applies to models that depend on the drift velocity of the current-carrying electrons exceeding some threshold value, since the current density scales as $B_0$ and the drift velocity is the current density divided by the background density. This scaling is consistent with observations that show the acceleration region in the 3000-6000 km altitude range, where the quantity $B_0/n$ maximizes. It is also consistent with FAST observations showing that acceleration occurs where the density is very low (e.g., Strangeway et al., 1998). However, previous work by Koskinen et al. (1990) had suggested that there was a significant cold plasma population at these altitudes, and Pottelette (presented at this meeting) has suggested that observations of electron acoustic waves imply a 3-10% population of cold electrons. These contradictory observations have yet to be resolved.

Traditional thinking in the upward current region is that the current density and potential drop are related by the Knight relation (Knight, 1973)

$$j_{\parallel} = n e v_{th,\parallel} \frac{B_2}{B_1} \left[ 1 - \exp \left( \frac{-xe\Phi/T_{se}}{1 + x} \right) \right]_{x = 1} \approx n e v_{th,\parallel} \frac{\Phi}{T_{Le}}$$

where $x = (T_{se}/T_{\perp e})/(B_2/B_1 - 1)$, $B_1$ and $B_2$ are the geomagnetic field at the source region and the ionosphere, respectively, and $\Phi$ is the potential drop along the geomagnetic field. The last form of this equation shows that it is linear in the potential drop for potentials in the 1-10 keV range. This linear relation, written as $j_{\parallel} \approx K\Phi$, has been the basis for the many theories of magnetosphere-ionosphere coupling. In this relation the magnetic mirror force plays an important role, and the current-voltage relation is based on magnetospheric electrons filling the loss cone. The entire auroral circuit was considered by Rönnmark (1999), who emphasized the low density in the acceleration region, and obtained a relation where the current density is proportional to $\Phi^{1/2}$. In the downward current region, the electrons are moving in a diverging magnetic field. Here filling of the loss cone is not essential, while the density profile might be relevant. For this region, Temerin and Carlson (1998) have developed a model that emphasizes the background ion density distribution, and have found a current-voltage relation that is roughly linear. Boström (1998, and this meeting) proposed a Child's law diode type relation, in which the current density scales as $\Phi^{0.7}$. Indeed, Janhunen and Olsson (2000) have even suggested that the potential drop is not really a function of the current density at all, and that the equipotential contours close above the acceleration region. Also, Torvén and Wendt (2000) have presented laboratory investigations which may be relevant to the formation of potential drops in space plasmas.

The relation of the global current-voltage relation to the microphysics of the auroral potential drop remains an open question. Many microscopic mechanisms, such as anomalous resistivity, magnetic mirror effects, strong and weak double layers and solitary waves, electron inertial effects, etc., have been proposed, but none of these models has been conclusively determined to be the dominant mechanism for parallel electric fields. On one level it is tempting to say that the microphysics does not really matter for the large-scale dynamics of the auroral zone, but on the other hand, one would hope that the detailed observations now available should be able to resolve the interesting plasma physics questions that arise with these mechanisms. One difficulty is that models of these phenomena have yet to be coupled to the large-scale dynamics of the auroral current systems; for example, computer simulations of double layers and solitary waves are generally done without considering the current system that provides the energy for these structures to form and accelerate particles. More work is clearly needed in both theory and observations in order to resolve these issues.

One area in which there has been considerable progress is in understanding the scale sizes of auroral current structures (e.g., Lysak and Song, 1999). The linear Knight relation, combined with current closure in the ionosphere, suggests a scale size given by $(\Sigma_P/K)^{1/2}$, which is about 100 km for typical parameters (e.g., Lyons, 1980). This scale size represents the largest scale on which field-aligned potentials can occur. Vogt and Haerendel (1998) have recently noted that when Alfvén wave dynamics are included, a new scale size $(\Sigma_A/K)^{1/2}$ is introduced, where $\Sigma_A = 1/\mu_0 V_A$ is the Alfvén admittance. This scale size, which is the order of 10 km for typical
parameters, represents the size below which Alfvénic structures become quasi-electrostatic. A third scale size is given by the electron inertial length $c/\omega_{pe}$, which is about 1 km mapped to the ionosphere. This is the scale at which Alfvén waves become dispersive, which would suggest this as a minimum size for current structures. However, in the presence of density gradients in the auroral zone, it has been shown (Lysak and Song, 1999) that Alfvénic structures can occur on even smaller scales. However, observations (e.g., Borovsky and Suszcynsky, 1993; Trondsen and Cogger, 1998; this meeting) have indicated that auroral arcs have scale sizes down to 10 m. These narrowest of auroral forms have yet to be explained in a satisfactory manner. One should be careful to note, however, that the wavelengths predicted by various theories are representative of the spacing between auroral arcs, not the thickness of an individual observed auroral arc, which is likely indicative of only the most intense currents in the structures.

4 The Ionosphere

The auroral ionosphere is a fascinating region in its own right, with the interplay of ionization from sunlight and from particle precipitation being considered in conjunction with a strong current system. A long-standing question is to what extent does the ionosphere control the dynamics of the auroral current system and the presence of visible aurora. The height-integrated conductivity of the ionosphere is well known to control the reflection of Alfvén waves from the ionosphere and the width of field line resonances, and to provide for ionospheric drag on the magnetospheric convection. Recently, Newell et al. (1996; 1998) have suggested that auroral acceleration is enhanced in regions where the ionosphere is in darkness, such that the electron precipitation is the major source of ionospheric ionization. Observations from FAST (e.g., Carlson, this meeting) indicate that the auroral currents are more structured at low altitudes than at higher altitudes, suggesting a role for the ionosphere as structuring auroral currents.

One mechanism that could satisfy these observations is the possibility of ionospheric feedback from the ionosphere (e.g., Atkinson, 1970; Sato, 1978; Lysak, 1991). This model considers the enhancement of the ionospheric conductivity by electron precipitation; the resulting modification of the current system by field-aligned currents flowing at the conductivity gradients can result in additional precipitation that, under the proper phase conditions, can give rise to an instability. This instability is damped by recombination when the background conductivity is low, which could explain the observations of Newell et al. This is another area in which further work needs to be done. The existing theories of the feedback instability all assume a height-integrated conductivity; however, at the small scale sizes of individual arcs, the structure of the ionosphere becomes important and the height-integrated assumption fails.

Another option is that the Newell et al. results reflect the density profile in the topside ionosphere. As noted in the previous section, parallel electric fields are easier to produce when the background plasma density is low. Under nighttime conditions, the topside scale height of the ionosphere is reduced, and so the plasma density in the acceleration region might be expected to be smaller. Recent Polar observations indicate that there are seasonal and diurnal dependences in the background plasma density at 6000 km altitude with the density being lower at night and in winter, supporting this point of view (J. Wygant, personal communication). The question of the relative roles of the ionospheric conductivity and density profile in auroral acceleration is one that requires both more observation as well as more theoretical work for its resolution.

Nevertheless, it appears likely that much of the structuring of the auroral currents that gives the aura its dynamic and beautiful appearance may be the result of the detailed interaction of the ionosphere with the auroral current system. Small-scale structures such as curls seem to have very small intrinsic time scales, suggesting that they do not reflect structures mapping all the way into the magnetosphere, but are rather localized between the ionosphere and the acceleration region.

In the following we discuss several microphysical phenomena, some of which may be of major importance also for the macrophysics in the auroral region.

5 Auroral Kilometric Radiation

Auroral Kilometric Radiation (AKR) is radio emissions with frequencies of typically a few hundred kHs generated inside the auroral acceleration region. The emissions can propagate and leave the magnetosphere, but observations from the source region are needed for understanding of the wave generation. Recent detailed observations by the FAST satellite (Strangeway et al., 1998; 2000; Ergun et al., 1998b, Delory et al., 1998) are consistent with earlier data from the S3-3 and Viking spacecraft. All observations are consistent with AKR generation at altitudes of a few thousand kilometers, in a region with
parallel electric fields both above and below the source region. Both upgoing ions and downgoing electrons with keV energies are observed in the AKR generation region. Furthermore, the cold electron population is almost entirely depleted, with around 1 cm$^{-3}$ of hot (above 100 eV) electrons being responsible for the bulk of the electron distribution. AKR is generated at frequencies within a few percent of the local electron gyrofrequency, and can have amplitudes up to a few hundred mV/m.

All major observed AKR features can be explained by the so-called Doppler-shifted cyclotron maser generation mechanism. This mechanism includes wave generation by positive slopes in the hot electron distribution, and also includes relativistic effects since the waves are emitted very close to the electron gyrofrequency. Positive slopes of the electron distribution in velocity space may be generated since downgoing and mirroring auroral keV electrons can not have low velocities inside the acceleration region. Also, additional anisotropies may be due to electrons trapped by the magnetic mirror force (below the AKR source region) and the parallel electric field (above), or by a loss cone in the mirroring electrons. Observations often show plateaus in the electron distributions at relevant velocities. A common interpretation is that fine structure in the source region and rapid velocity space diffusion of the electrons caused by AKR prevents the detection of large anisotropies.

AKR is not a smooth, continuous emission, but has a lot of fine structure. The cause of this fine structure is not known, but non-linear effects, and emissions from small moving solitary structures may be important (Pottelette, this meeting).

6 Ion Energization and Associated Waves

Many spacecraft observations show that ions in the ionosphere and magnetosphere can be energized perpendicularly to the geomagnetic field. These ions can then move upward along the inhomogeneous magnetic field, and form so-called conics in velocity space. These upflowing ions constitute an important source of magnetospheric plasma (Moore et al., 1999; Hultqvist et al., 1999). Some of the ions are further accelerated upward by the same electric fields that accelerate auroral electrons downward, and these ions then form ion beams. Most of the perpendicular energization takes place above the collisional ionosphere, and thus depends on interaction between the charged ions and some (often time-varying) electric field. In the important region from the collisional ionosphere (a few hundred kilometers), to altitudes of several thousand kilometers, it is now becoming clear which wave spectra are typically associated with ion conics.

Statistical studies of wave and particle data from the Freja satellite at altitudes around 1700 km show that the most common ion heating mechanism, leading to most of the ion outflow, is associated with broadband low-frequency electric and magnetic wave fields occurring in the auroral region at all local times (André et al., 1998). This energization gives the highest average ion energies (hundreds of eV on the nightside), and the highest outflows (more than $10^{13}$ ions/(s-m$^2$) in the prenoon sector). During specific events, typically in the premidnight auroral region and associated with downgoing keV auroral electrons, lower hybrid or electromagnetic ion cyclotron (EMIC) waves may dominate the ion energization. The most intense ion energization (average ion energies of a few keV) observed by FAST at altitudes of a few thousand kilometers is associated with the “fast solitary structures” discussed below (Carlson et al., 1998; Ergun et al., 1998c). The importance of this heating for the total ion is not yet clear.

EMIC waves may be generated by downgoing keV electrons at frequencies below the He$^+$ and H$^+$ gyrofrequencies, often in the premidnight sector (Lund et al., 1999). These waves may locally cause helium ions to be a few times more energetic than protons and oxygen ions.

Lower hybrid waves, typically at a few kHz, may also be generated by downgoing keV electrons. These waves may occur in large regions, with scale lengths of at least hundreds of kilometers in the direction perpendicular to the geomagnetic field. At altitudes around 2000 km, such lower hybrid waves may locally cause most of the outflow of both H$^+$ and O$^+$ ions. Up to these altitudes, lower hybrid waves are sometimes observed to be concentrated in lower hybrid solitary structures (LHSS) inside filamentary density cavities. These cavities are about 50–100 m wide in the direction perpendicular to the geomagnetic field, and probably much longer in the parallel direction. The LHSS observed around 1000 km by sounding rockets, e.g. Topaz 3 and AMICIST, are associated with perpendicular ion energization to average energies of about 10 eV. Observations by the Freja satellite confirm the existence of LHSS around 1700 km altitude, but no obvious ion energization is associated with the structures at these altitudes. Some sounding rocket LHSS observations, e.g. by PHAZE 2, show counterrotating electric field structures at frequencies above and below the lower hybrid frequency $f_{LHR}$ of the plasma outside the cavity (e.g. Bonnell et al., 1998). The presence of waves below $f_{LHR}$ indicates that waves are trapped in the cavity. The waves could be trapped in a pre-existing den-
sity cavity, or LHSS could be the result of a soliton collapse process. A statistical study of Freja data indicate that the observed LHSS and density cavities are unlikely to be explained by a collapse theory for lower hybrid waves (Hoymork et al., 2000).

Most of the intense perpendicular ion energization observed by Freja around 1700 km occurs in regions of broadband low-frequency electric and magnetic wave fields. These waves cover frequencies from less than one Hz up to at least several hundred Hz, i.e., above the proton gyrofrequency. A similar correlation is observed by FAST at altitudes of a few thousand km (Carlson et al., 1998; Lund et al., 1999) and by sounding rockets. Assuming resonant transfer of energy from the waves around the gyrofrequency to O\(^+\) ions, often only a few percent of the observed wave power needs to be in resonant with the ions to obtain the observed O\(^+\) energies (André et al., 1998). However, the wave spectral density is decreasing with frequency. Thus, one might expect less heating of lighter ions such as protons with less wave power near their gyrofrequency. Still there are several observations showing nearly the same energy of ions such as H\(^+\) and O\(^+\). One phenomenon that can explain several such events is the existence of a downward electric field at altitudes of a few thousand kilometers in the region of upward accelerated electrons (the return-current region). This so-called pressure cooker field will keep the ions inside a low altitude ion heating region until the perpendicular heating and the magnetic mirror force can overcome the downward force from the electric field (Lund et al., 2000). Since all ions must overcome the same electric field, all ion species must be heated to the same energy. It is still not clear how common the pressure cooker effect is, for example, on the dayside of the magnetosphere.

At higher altitudes, above 20000 km, recent observations by the Polar satellite indicate that sometimes the heated ion distributions are toroidal in velocity space, i.e., there are no particles near zero perpendicular velocity (Huddleston et al., 1999). Possibly the presence of solitary wave structures, rather than incoherent wave fields, are important for the formation of these distributions.

Although the correlation between broadband low-frequency waves and ion heating is well documented, the generation and nature of these waves is less well understood. One way of investigating these waves is to use two separated electric field antennas on a single spacecraft as a plasma wave interferometer. (The same type of antenna system was used to investigate rotating electric fields in LHSS, as discussed above.) Considering the low coherence between broadband waves detected by two antennas on PHAZE 2, and also on TOPAZ 3, with antenna separations of 3 m and 6 m respectively, it was concluded that the wavelength was of the order of the antenna separation length (Kintner et al. 1999). The O\(^+\) gyroradius was also of the order of a few meters. Considering the observed spectral features, and estimated wavelengths, it is far from obvious that any wave mode in a homogeneous plasma can explain the observations. Ion acoustic waves could possibly be a candidate at higher altitudes of a few thousand kilometers in regions of electron beams, if the electron temperature is much higher than the ion temperature. However, these sounding rocket observations indicate that although Doppler shift due to the spacecraft motion alter the observed fields, truly time-varying fields are present in the plasma. This is in contrast to investigations of the broadband waves using electric and magnetic fields observed by Freja (Stasiewicz, 1999a,b). Considering the ratio of the electric (E) and magnetic (B) fields, it can be shown that this ratio is consistent with the observed broadband fields being due to Doppler shift, caused by the satellite motion, of nearly static structures over a wide range of spatial scales. The nearly static structures would be due to Alfvén waves close to zero frequency, and the appropriate dispersion relation predicts the E/B ratio. Also, in this scenario, the ion heating is not caused by a time-varying field, but rather by ion motion in static field structures. The interpretations of the broadbanded waves based on sounding rocket and on Freja data appear contradictory, and further investigations are needed.

One way of investigating wave properties is to use the technique of wave distribution functions (WDFs). Observations at a specific frequency of several of the total of six electric and magnetic wave components are used. Rather than using multiple antennas, extra information is obtained by comparing the observed polarization with predictions from some dispersion relation. Usually the approximation of linear waves in an infinite, homogeneous and magnetized plasma is used. The problem of finding the distribution of wave energy in wavevector space is underdetermined, but by various techniques an estimate can be obtained. Two independently developed methods for reconstructing the WDF are presented by Oscarsson et al. (2000). These results concern waves with the same frequency, but on two different wave modes near the proton gyrofrequency.

Again considering the broadband low-frequency waves associated with ion energization, it is not clear how these waves are generated. Assuming that truly time-varying fields near the ion gyrofrequencies are involved, the observed field-aligned currents seem too weak to cause wave generation (André et al., 1998; Kintner et al., 1999). One possible explanation is...
that effects in an inhomogeneous plasma are important. For example, spatial structure in a static perpendicular electric field would give gradients (shear) in the perpendicular plasma drift (Ganguli and Palmadesso, 1988). Sharp gradients would directly lead to waves, and weaker gradients would decrease the current needed for wave generation. Also, the ordering of spectral features by the ion gyrofrequencies can be “smeared out”, leaving a broadband spectrum, as observed. These waves might be more consistent with the detailed sounding rocket observations than wave modes in a homogeneous plasma. Laboratory plasma experiments designed to imitate space conditions as far as possible, confirm that shear can facilitate wave generation (Koopke et al., 1999). There is no doubt than inhomogeneities can be important for wave generation. The question is now how important shear is for the generation of broadband waves in the magnetosphere and for the subsequent ion energization.

7 Solitary Waves

Many solitary waves (SWs) have been observed in the auroral region and in other parts of the magnetosphere. We use the word solitary, rather than soliton, since the latter term would imply specific mathematical properties of the fields that usually can not be strictly verified from observations. Often SWs can be detected as structures with converging or diverging electric fields, corresponding to “clouds” of negative or positive charge, respectively. These structures are moving up or down along the geomagnetic field. Their velocity can often be determined by comparing observations from two separated antennas on a satellite. Integrating the electric field parallel to the geomagnetic field, many SWs can be shown to have a net potential drop that is essentially zero. The observed perpendicular electric field may be close to zero, or may be directed in mainly one direction. Positive charge clouds are often interpreted as a lack of negative electrons. This is partly based on the velocity of these SWs being comparable to electron rather than ion velocities, and is not always unambiguous. Similarly, negative charge clouds are often believed to be caused by a lack of ions. Some theoretical aspects of SWs are discussed by Roth and Muschietti (2000) and Raadu (2000). Below we consider some SWs recently observed in the magnetosphere, and start by discussing positive charge structures.

Solitary waves consistent with positive charge structures have been observed by FAST in the auroral return current region at altitudes of a few thousand km. The SWs are found together with upgoing field-aligned electrons with energies of hundreds of eVs to keVs. The SWs are observed to be around 500 m (one or a few Debye lengths) along the geomagnetic field and have probably about the same extension in the perpendicular direction (Ergun et al., 1998c; Roth and Muschietti, 2000). They are propagating upward/anti-Earthward at velocities of about 500–5000 km/s, a significant fraction of the electron beam velocity, and are often called “fast solitary waves”. Typical amplitudes are 50–1000 mV/m. The potential may reach 100 V, but the parallel net potential drop over the structure is much smaller or zero. The detected magnetic signature is consistent with that of a moving particle cloud with the observed charge and velocity. The solitary structures may be generated by the electron beams. They can modulate electron fluxes, and may help support an electric field accelerating the electrons upward. The structures may also cause perpendicular ion energization to keV energies.

Solitary waves corresponding to a positive charge structure have also been observed at altitudes of a few Earth radii in the cusp and plasma sheet boundary layer (Cattell et al., 1999; 2000; Mozer et al., 1997). These observations by the Polar satellite often show upgoing/anti-Earthward SWs, but such waves associated with downward/Earthward particle injections in the cusp are propagating downward. Typical velocities of the SWs are around 1000 km/s, amplitudes are up about to 50 mV, the potential is up to about 1 V, while the net potential drop is small or zero. Some of the highest amplitude SWs have a detectable magnetic field. The parallel size varies from hundreds of meters to several kilometers depending on plasma parameters. This typically corresponds to 10’s of Debye lengths. The SWs are likely to be an electron mode, i.e. due to a lack of electrons, but the possibility of an ion mode at these altitudes is still being considered. (Cattell et al., 1999).

Somewhat similar SWs have also been detected in the magnetotail at distances at least out to 200 Earth radii (Kojima, 1999; Matsumoto et al., 1994; 1999). These observations by the GEOTAIL satellite show structures with amplitudes of up to a few hundred \( \mu \text{V/m} \), a potential of up to a few V, and a net potential drop near zero. These structures are often called electrostatic solitary structures. Observations do not show a perpendicular electric field at larger distances from Earth, while such fields often are found at smaller distances. By comparing with electron observations and computer simulations, the velocity is estimated to be around \( 10^4 \text{ km/s} \). Similarly, the parallel size is around 30 km. The SWs are probably generated by electron beams with energies of several hundred eV.

The electric fields of the solitary structures observed by GEOTAIL had previously been observed by other spacecraft, but only by using various kinds of fil-
ters giving wave intensity in various frequency bands. The obtained spectra were broadband, and the emissions were called broadband electrostatic noise (BEN). It was assumed that the spectra corresponded to incoherent wave fields, but the GEOTAIL instruments showed that the wave form rather corresponded to solitary structures. However, the observed waveforms of the broadband low-frequency waves associated with the most common ion heating in the auroral region often correspond to rather incoherent fields.

As opposed to the positive potential structures discussed above, also SWs corresponding to negative potential structures have been observed in the magnetosphere. Such SWs were observed by the S3-3 and Viking satellites at altitudes around 10,000 km in the auroral region (Temenin et al., 1982; Boström et al., 1988). The Viking observations indicated SWs with parallel electric fields up to about 10 mV/m, a parallel size of a few hundred meters, and an upward velocity of 5–50 km/s. These SWs were found in regions of upgoing ion beams with energies of up to about 1 keV. Observations also indicated the presence of a significant amount of cool (few eV) plasma in these regions (Koskinen et al., 1990). This gives a parallel size of the SWs of 5–50 Debye lengths. Several of the SWs were interpreted to have a parallel net potential drop of about 1 V, corresponding to an upward electric field, and were referred to as weak double layers (WDLs). However, the WDLs were not believed to be important for the total auroral potential drop.

Recent observations of SWs corresponding to positive potential structures have been obtained by FAST in the auroral region at altitudes of a few thousand kilometers (McFadden, this meeting). The FAST observations are also from regions of upgoing ion beams. However, the SWs have much higher velocities than those detected by Viking. This is consistent with the observation that essentially no cool plasma seems to be present in these regions (McFadden et al., 1999). There are simply no low velocity particles than can cause a slowly moving charged structure. There is still a discussion concerning how much of the differences between Viking and FAST conclusions are due to instrumental difficulties and data interpretation, and how much is due to different geophysical conditions, for example caused by observations at different altitudes.

8 Conclusions

Several particle acceleration and wave generation phenomena have been observed in the auroral region. Some mechanisms are believed to be basically understood, such as the major features of AKR generation. For other important phenomena, there is no consensus concerning the basic mechanisms. This includes the downward acceleration of auroral electrons to keV energies, and the wave mode and generation of the broadband waves associated with much of the energization and outflow of ionospheric ions. The generation of various types of solitary waves, and their subsequent importance for particle acceleration, is also being investigated. Further observations, and theoretical and simulation efforts, are needed to understand the plasma physics of the auroral region. Eventually this research should guide us when investigating space plasma physics in other parts of the Universe.

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