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Quiet, Discrete Auroral Arcs: Acceleration Mechanisms

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Abstract The theory of the acceleration of auroral particles is reviewed, focusing on developments in the last 15 years. We discuss elementary plasma physics processes leading to acceleration of electrons to energies compatible with emission observed for quiet, discrete auroral arcs, defined as arcs that have time scales of minutes or more and spatial scales ranging from less than 1 km to tens of kilometers. For context, earlier observations are first described briefly. The theoretical fundamentals of auroral particle acceleration are based on the kinetic theory of plasmas, in particular the development of parallel electric fields. These parallel electric fields can either be distributed along the magnetic field lines, often associated with the mirror geometry of the geomagnetic field, or concentrated into narrow regions of charge separation known as double layers. Observations have indicated that the acceleration process depends on whether the field-aligned currents are directed away from the Earth, toward the Earth, or in mixed regions of currents often associated with the propagation of Alfvén waves. Recent observations from the NASA Fast Auroral SnapshoT (FAST) satellite, the ESA satellite constellation Cluster, and the Japanese Reimei satellite have provided new insights into the auroral acceleration process and have led to further refinements to the theory of auroral particle acceleration.

Keywords Aurora · Particle acceleration · Magnetosphere · Ionosphere

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1 Historical Introduction

Observations of the discrete aurora have been made since ancient times, leading to many fanciful descriptions speculating about their source. Much of this folklore has been summarized in the book of Eather (1980). Scientific study of the phenomenon began during the Renaissance, with Galileo being credited with introducing the term *aurora borealis*, or "northern dawn." Gauss noted that strong aurorae were associated with deflections of the compass needle, tying the aurora to magnetic phenomena. With the coming of the 20th century, Kristian Birkeland studied the aurora extensively from northern Scandinavia, making "terrella" experiments to show that magnetic fields could funnel charged particles into the polar regions (e.g., Jago 2001). Birkeland postulated that the aurora was associated with a system of field-aligned currents, which now bears his name.

The International Geophysical Year (1957-1958) led to more detailed measurements tying the auroral emissions to the acceleration of charged particles. Observations of auroral X-rays from sounding rockets (Van Allen 1957) and balloons (Winckler et al. 1958) indicated that the aurora was associated with high energy particles, with Winckler et al. (1958) noting that the results seemed consistent with an acceleration mechanism close to Earth. A direct measurement of the auroral particles from a sounding rocket (McIlwain 1960), who noted that the aurora was associated with "nearly monoenergetic electrons" with an energy of 6 keV, concluding that "the presence of the monoenergetic electrons strongly suggests an electrostatic acceleration mechanism." On the theoretical side, Alfvén (1958) and Alfvén and Fälthammar (1963) proposed that electric fields parallel to the magnetic field could exist in a magnetic mirror geometry when electrons and protons had different pitch angle distributions. Alfvén (1958) proposed the term "double layer" for the localized parallel electric field associated with constrictions in a laboratory plasma column, and suggested that such structures could form at the interface between hot and cold plasmas, such as the plasma sheet and the ionosphere (see review by Fälthammar 1979).

A further period of progress in the understanding of auroral acceleration came with the advent of polar-orbiting satellites. Particle observations from the low-altitude Injun-5 satellite showed that the "monoenergetic" peak in the electron distribution rose in energy to a peak and then fell, showing a structure that in energy-time spectrograms looked like an "inverted-V" (Frank and Ackerson 1971; Gurnett and Frank 1973). This led Gurnett (1972) to postulate U-shaped equipotential structures to explain this acceleration mode. This type of structure was confirmed by the S3-3 satellite, which had a higher orbit with an apogee of 8000 km (Mozer et al. 1977, 1980). Particle measurements from S3-3 were found to be consistent with quasi-static acceleration (Mizera and Fennell 1977; Croley et al. 1978). The electric field experiment on S3-3 measured large (>100 mV/m) perpendicular electric fields above the aurora. The electrostatic nature of these structures was verified by Temerin et al. (1981) who noted that for higher altitude cases, the potential found by integrating the perpendicular electric field observed by the satellite was equal to the energy of the upgoing ion beam at the center of the structure.

Theoretical models of the acceleration process also were developed in the 1970's. Knight (1973; see also Lemaire and Scherer 1973; Fridman and Lemaire 1980; Lyons 1980) considered the motion of electrons in magnetic mirror geometry in the presence of a parallel potential drop and found that for typical auroral energies (1-10 keV), there was a linear relationship between the current density and the total potential drop, which can be written as $j_\| = K\Phi$. Considering this relationship and assuming that the field-aligned currents were closed by Pedersen currents in the ionosphere, gave a characteristic scale length of $\sqrt{\Sigma_P/K}$. This scale length is about 100 km for typical parameters (e.g., $\Sigma_P = 10$ mho and

$K = 10^{-9}$ mho/m^2). This is at the upper end of the scale sizes observed in auroral structures (Karlsson et al. 2020). The Knight relation was supported by the sounding rocket observations of Lyons et al. (1979). This type of model was further developed by Chiu and Schulz (1978) and Chiu and Cornwall (1980) who made self-consistent models satisfying Poisson's equation. Models based on the concept of anomalous resistivity due to wave-particle interactions were considered (e.g., Papadopoulos 1977), although definitive evidence of this effect remains elusive. The theory of double layers in terms of BGK modes was developed by Block (1972) and Knorr and Goertz (1974), and double layers in which the electric field was oblique to the magnetic field were considered by Swift (1975, 1979), who called them electrostatic shocks. The distinction between double layers and electrostatic shocks was debated, with Goertz (1979) concluding that double layers were stationary with respect to the plasma while electrostatic shocks moved; however, this distinction has largely faded from the literature and such structures are now mostly called double layers.

All of these models were electrostatic in nature and did not address the formation and evolution of the parallel electric fields. The enhancement of the field-aligned current required for the development of parallel electric fields is largely due to the electromagnetic nature of wave energy propagation along the field lines, generally carried by Alfvén waves. Mallinckrodt and Carlson (1978) considered an Alfvén wave generated by a source moving with respect to the plasma and showed that the reflection of this wave from the ionosphere produced paired electric field structures like those observed by S3-3 without invoking a parallel electric field. Hasegawa (1976) considered mode conversion at the plasma sheet boundary layer from a surface Alfvén wave to a so-called kinetic Alfvén wave by including electron pressure and finite ion gyroradius effects, the former of which leads to parallel electric fields. Goertz and Boswell (1979) noted that the effect of electron inertia was more important than electron pressure in cold plasmas like the topside ionosphere. This effect would later be invoked to explain the broadband electron distributions observed by Freja (Louarn et al. 1994) and FAST (Chaston et al. 2002). Furthermore, Lysak and Dum (1983) showed that in the presence of a localized anomalous resistivity, a propagating Alfvén wave could evolve into a quasi-static potential structure.

The effects of kinetic Alfvén waves propagating obliquely to the magnetic field was considered by Haerendel (1983), who developed a "fracture" model that included the proper motion of the arc with respect to the plasma, or equivalently the motion of the plasma across the arc. In his model, a parallel electric field developed due to an anomalous resistivity region that diffused across the plasma. A steady-state oblique arc model was further developed by Seyler (1988, 1990), who considered the nonlinear evolution of the flux tube in which electron inertia gave rise to parallel electric fields. He invoked a tearing instability operating on the perturbed magnetic field to structure auroral currents. A similar steady-state convecting arc model was developed by Knudsen (1996), who showed that structures on the order of tens of electron inertial lengths could be self-consistently established. However, this model did not include the effects of ionospheric coupling that should play an important role in the evolution of auroral arcs.

Greater understanding of the nature of the auroral acceleration region has been provided by a number of satellites, including Dynamics Explorer (Burch et al. 1981), Viking (Hultqvist 1987), Freja (Lundin et al. 1994), Akebono (Tsuruda and Oya 1993) and FAST (Carlson et al. 1998a, 1998b). This work is described in more detail later in this manuscript. This review focuses on the acceleration mechanisms linked to quiet, discrete auroral arcs. This class of auroral forms is widely encountered and can be considered as a "prototype", fundamental paradigm for all other types of aurora. In coherence with Borovsky et al.

(2020), we define a quiet arc as the one "not associated with dynamic events such as substorm breakup, and which has lifetimes ranging from several minutes to hours." The remainder of this article will detail the advances in our understanding of the auroral acceleration mechanism since the publication of the previous book (Paschmann et al. 2003) as well as some key aspects not fully discussed in the previous review. As in the previous article (Karlsson et al. 2020), we will consider discrete arcs as being associated with the precipitation of accelerated particles that are stable on time scales of minutes or longer.

2 Theoretical Framework for Quasi-Static Acceleration Processes

One of the most challenging issues in theory of auroral acceleration is how to sustain the parallel electric field with spatiotemporal scales relevant to auroral phenomena in collisionless plasma (e.g., Song and Lysak 2006, 2015). The parallel electrostatic field is shielded by thermal electrons in spatial scales longer than the Debye length λ_D, while the Debye shielding is established in a time scale of electron plasma oscillation. Therefore, electrostatic phenomena involving charge separation such as double layers are characterized by short spatial and temporal scales. On the longer spatiotemporal scales, the electrostatic potential energy leaking out of the shielding is smaller than the electron thermal energy (i.e., $|e\varphi/k_B T_e| < 1$), where the quasi-neutrality (or, simply, the charge neutrality) condition of $\sum_s q_s n_s = 0$ is well satisfied. Here, q_s and n_s mean the charge and the number density of particle species of s. Note that quasi-neutrality does not imply that the parallel electric fields are strictly zero. In the presence of current flows, a weak parallel electric field can exist over larger scales, as is discussed in Sect. 3.

In the kinetic Vlasov approach one adopts a statistical description of plasma dynamics and considers the microscopic structure of auroral (magnetospheric and ionospheric) plasmas at the level of velocity distribution functions (VDFs) of electrons and ions, f_e and f_i. In the general case the VDFs are functions of time and of the six components of the phase space (three position and three velocity coordinates, respectively). The Vlasov equation describes the spatio-temporal evolution of f_e and f_i and is derived from the general Boltzmann equation by neglecting the close range (binary) interactions between particles and by considering electromagnetic forces.

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \frac{\partial f_\alpha}{\partial \mathbf{r}} + q_\alpha (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_\alpha}{\partial \mathbf{v}} = 0 \tag{1}$$

where f_s is the VDF of species s, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic field. The Vlasov equation is "coupled" to the full Maxwell set of equations describing the electromagnetic field. The coupling is mutual in the sense that the solutions of Maxwell's equations are considered in the force term of the Vlasov equation while the charge and current densities of each species, the "sources" of the Maxwell set, are evaluated from the moments of the VDF:

$$Q_\alpha^{(ijk)} = \iiint v_x^i v_y^j v_z^k f_\alpha \left(v_x, v_y, v_z \right) dv_x dv_y dv_z \tag{2}$$

where $q_\alpha Q_\alpha^{(000)}$ gives the charge density of species a, $q_\alpha Q_\alpha^{(100)}$ gives the J_x component of the current density, etc. The above expression for the moments is given in a canonical representation as an integral in the velocity space; note, however, that a representation in the space of constants of motion (e.g. total energy, canonical momenta) is fully equivalent (Lemaire and Scherer 1970; see also Khazanov et al. 1998). The kinetic Vlasov treatment of the particle dynamics in mirroring magnetic fields, as is typical for the auroral regions, allows for a self-consistent estimation of the relationship between the moments of the VDF and the electric potential. An example is the well-known current-voltage relationship provided by various models for upward and downward field-aligned currents. Non-thermal effects, like the role of kappa VDFs can also be quantified. Note also that the Vlasov equation gives a valid description of plasma processes with characteristic time and space scales shorter than the mean free time and the mean free path. A linearization of the Vlasov equation allows for study of various class of waves and their respective dispersion relation in magnetoactive plasmas (as is the case for the auroral regions) with or without thermal effects.

While the Vlasov approach gives the most complete and self-consistent description of the plasma, application of this approach is generally restricted to time-independent situations (e.g., Echim et al. 2007). This is due to the fact that Vlasov models should resolve the Debye length and plasma frequency time scales, which are 74 m and 0.1 ms, respectively, for a plasma with a temperature of 100 eV and a density of 1 cm^{-3}. Global scale hybrid-Vlasov models are now being developed (e.g., Palmroth et al. 2015) which treat the ions by a Vlasov model while the electrons are a neutralizing fluid. However, these results are still preliminary. The difficulty of these models to model the global dynamics has led many researchers to adopt fluid models of the magnetosphere.

The magnetohydrodynamic (MHD) equations are the most popular set of equations for describing low frequency and macro-scale plasma phenomena where the charge neutrality is assumed. Since MHD is based on a single fluid approximation, it does not directly describe the auroral electron acceleration; however, it is an important theoretical framework to describe Alfvén waves in the magnetosphere. The Ohm's law in the MHD equation tells us that the parallel electric field vanishes in the ideal MHD limit with no resistivity (that is, $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$ where $\boldsymbol{E}$, $\boldsymbol{V}$, and $\boldsymbol{B}$ denote the electric field, flow velocity and the magnetic field, respectively). The Ohm's law derived from the equation of motion for electrons is generalized by taking into account higher order terms neglected in the ideal MHD, such as the electron inertia, the electron pressure gradient, and the Hall terms as well as a finite ion gyroradius effect. By means of the generalized Ohm's law, one can discuss generation of the inductive parallel electric field associated with the kinetic and/or inertial Alfven waves.

Further reduction of the MHD equation is also useful in application to the auroral region with the strong background magnetic field B_0. The reduced MHD equations (e.g., Hazeltine and Meiss 1992) are often used to decouple the shear Alfven waves from the fast and slow compressional modes, where only the parallel component of the vorticity and the vector potential (flux function) are retained to describe the shear Alfvén dynamics. The derivation is done by assuming the flute ordering of

$$\frac{L_\perp}{L_\parallel} \sim \frac{B_1}{B_0} \sim \frac{V}{V_A} \sim O(\varepsilon) \tag{3}$$

where $L_\perp$ and $L_\parallel$ are the perpendicular and parallel scale lengths of fluctuations, B_1 is the perturbed magnetic field, V means the flow velocity, V_A denotes the Alfvén speed, and ϵ is a smallness parameter. The reduced MHD equations are used to describe MHD instabilities (such as the kink, ballooning, and tearing instabilities) as well as the Alfvénic coupling of the magnetosphere and the ionosphere (e.g., Lysak 1991; Watanabe 2010). The parallel component of the generalized Ohm's law can also be incorporated into the reduced MHD equations.

In order to investigate interactions of electromagnetic fields and electron motions, one may return to the two-fluid equations before taking summation over particle species in derivation of the MHD equation where assumption of the charge neutrality is still useful to avoid the high-frequency plasma oscillation. In the two-fluid model, the displacement current term ($\epsilon_0 \partial \boldsymbol{E}/\partial t$) is often retained, and plays a role in a low density region where V_A/c is non-negligible (e.g., Lysak 1993; Streltsov and Lotko 2003). This condition is often met in the auroral density cavity at altitudes of 1 $\mathrm{R_E}$ or less where the magnetic field is strong and the density is low. The displacement current term related to the parallel electric field is often neglected; however, it is critical for the development of the charge separation necessary to form structures like double layers (Song and Lysak 2001a, 2001b, 2006).

Here, we must recall that it may not be straightforward to derive two-fluid equations from the set of Vlasov-Poisson (or Vlasov-Maxwell) equations by taking fluid moments of the kinetic equation unless suitable closure relations are given. Hammett and Perkins (1990) developed a kinetic fluid closure model (called the Hammett-Perkins or the Landau closure) which mimics the phase relation between the parallel heat flux and the temperature perturbation given by the linearized Vlasov-Poisson system so that the Landau damping is effectively included.

Any fluid equations, however, cannot describe the particle acceleration process self-consistently with formation of the parallel electric field, while a test particle calculation in the electromagnetic fields given by the fluid models may be fruitful to estimate the amount of possible acceleration (e.g., Chaston et al. 2002; Lysak and Song 2005). This is why a kinetic description is essential to the auroral electron acceleration. The gyrokinetic equations (Rutherford and Frieman 1968; Antonsen and Lane 1980; Frieman and Chen 1982; a recent review for the modern gyrokinetic equations is found in Brizard and Hahm 2007) applicable to the low frequency phenomena have been derived in studies of drift wave instabilities and turbulence in magnetically confined plasma under the ordering of

$$\frac{\rho}{L} \sim \frac{L_\perp}{L_\parallel} \sim \frac{\delta f}{F_0} \sim \frac{e\Phi}{k_B T} \sim \frac{B_1}{B_0} \sim O(\varepsilon) \tag{4}$$

where L, ρ, δf, F_0, ϕ, and T denote the scale length of the system, thermal gyroradius, perturbed and equilibrium distribution functions, electrostatic potential, and temperature, respectively. The perturbed distribution function is averaged over the gyromotion, and is defined as a function on the five-dimensional phase space, such as $\delta f(\boldsymbol{X}, v_\parallel, \mu)$, where $\boldsymbol{X}$, $v_\parallel$, and μ represent the gyrocenter position, the parallel velocity component, and the magnetic moment, respectively. The gyrokinetic equations describe time-evolution of δf along trajectories of charged particles with $\boldsymbol{E} \times \boldsymbol{B}$, curvature, and ∇B drift motions and the mirror force. Perturbations of the electromagnetic fields are given by solving the Poisson equation and the Ampere's law with effects of finite gyroradius and polarization. It is noteworthy that the gyrokinetic ordering given above has a similarity to that used in derivation of the reduced MHD equation. It means that the gyrokinetic equations are a kinetic extension of the reduced MHD equations relevant to low frequency phenomena. Actually, the gyrokinetic theory has been applied to auroral electron acceleration by the kinetic Alfvén waves amplified through the feedback instability in the magnetosphere-ionosphere coupling (Watanabe 2014). In a limit of small $\rho/L_\perp \ll 1$ (that is, a limit of long perpendicular wavelength), one finds that the drift kinetic equations are derived from the gyrokinetic equations. The former is often applied to study of electron dynamics in low frequency waves such as the inertial (or dispersive) Alfvén waves (Watt et al. 2004; Watt and Rankin 2009).

Finally, it is remarked that velocity-space integrals of the gyrokinetic equations lead to the gyrofluid equations for each particle species. Relevant closure relations are required to truncate the moment hierarchy, not only for the parallel heat flux but also for

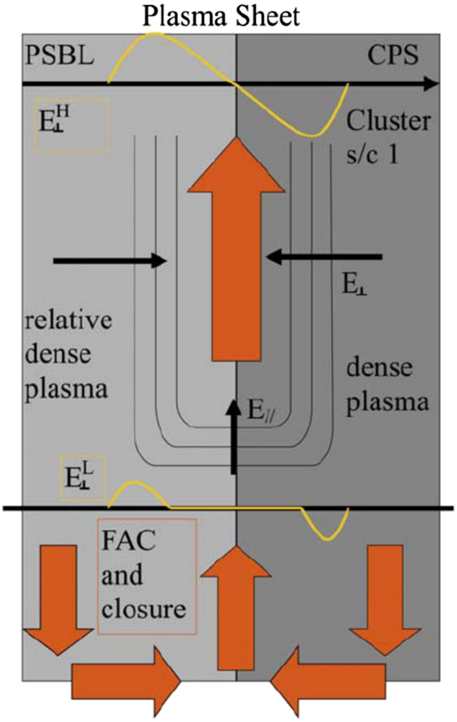


Fig. 1 A diagram of the auroral current circuit sustained by a magnetospheric generator at the interface between the plasma sheet and the plasma sheet boundary layer. The diagram also illustrates the current closure in the upper ionospheric layers (adapted from Marklund et al., 2007)

the magnetic drift term and the finite gyroradius correction (Dorland and Hammett 1993; Beer and Hammett 1996). Application of the gyrofluid equations for the auroral particle acceleration is, however, still immature so far.

3 Quasi-Static Acceleration in the Upward Current Region

A quiet discrete arc is connected by magnetic field lines to a high-altitude generator that supplies an electromotive force in the electric circuit feeding the arc. Such an equivalent circuit is a simplified view of the magnetosphere-ionosphere coupling in auroral regions. Nevertheless, it allows for a description of the main features relevant for a quiet, discrete arc: (i) a magnetospheric generator, (ii) an upward current branch, (iii) an ionospheric load corresponding to the arc itself, (iv) a downward current region to close the circuit (see Fig. 1). In this section we discuss the acceleration of particles in the upward current leg of the auroral circuit. Magnetospheric electrons moving downward along auroral magnetic field lines are accelerated and precipitate into the outer ionospheric layers where they dissipate the energy (mainly through collisions with the ambient neutral gas) and trigger optical auroral emissions. As mentioned in the historical introduction of this chapter, the observed kinetic properties of the precipitating electrons can give a hint on the acceleration mechanism. Indeed, it is believed that inverted-V spectra result from acceleration by a quasi-static parallel electric field (see details on the experimental evidence in the last section of this chapter).

The existence of an electric field component parallel to the magnetic field in a collisionless magnetized plasma is intriguing at a first sight since the electrons and ions have large mobility (virtually infinite) along magnetic field lines, thus is tempting to think that any electric charge imbalance would be immediately neutralized. Nevertheless, a kinetic treatment of particle dynamics in the Vlasov approach reveals the internal plasma mechanisms leading to the formation of such electric field structures and, for some simplified cases, provides a quantitative estimation of the parallel electric field. Let us follow a recent review of auroral acceleration (Birn et al. 2012) and discuss the main mechanisms for quasi-static parallel electric fields in the region of auroral upward field-aligned currents (see also Boström 2003, 2004).

3.1 Acceleration by Distributed, Charge Neutral, Large Scale Parallel Electric Fields

A distributed large scale parallel electric field is set-up in an auroral magnetic flux tube as a result of the effect of the mirroring magnetic field on the dynamics of electrons and ions moving upward/downward along the magnetic field lines (Boström 2003). As mentioned in the introductory historical notes, Alfvén and Fälthammar (1963) were the first to estimate the parallel component of the electric field due to electrons and ions moving in such a mirroring geometry. They found an analytic expression for $E_\parallel$ that depends on (i) the pitch angle anisotropy of ions and electrons and (ii) the rate of variation of the magnetic field intensity with the altitude. Nevertheless the validity of the expression postulated by Alfvén and Fälthammar (1963) is limited by the assumption that magnetospheric electrons and ions are monoenergetic (i.e. their velocity distribution function is a delta function). The Vlasov equation allows for an estimation of the parallel component of the electric field. In the case of a one-dimensional mirroring magnetic field configuration a general expression of $E_\parallel$ is given by (Persson 1966):

$$E_\parallel = \frac{m_\alpha}{e}\left[\frac{v_\perp}{2B}\frac{dB}{ds}\left(v_\perp \frac{\partial f_\alpha}{\partial v_\parallel} - v_\parallel \frac{\partial f_\alpha}{\partial v_\perp}\right) - v_\parallel \frac{\partial f_\alpha}{\partial s}\right]\left(\frac{\partial f_\alpha}{\partial v_\parallel}\right)^{-1} \tag{5}$$

where s is the coordinate in the direction parallel to the magnetic field. Obviously one needs to obtain the same value of $E_\parallel$ from the Vlasov treatment of each species α, electrons and ions. An additional constraint is quasi-neutrality, i.e. charge balance between electrons and ions.

A general solution for the parallel component of the electric field is not easy to find analytically. In fact, as noted by Persson (1966), if f_α does not depend explicitly on s but implicitly through the electric potential, $\Phi(s)$, then equation (5) is a tautology. General solutions of (5) for two or three dimensional configurations are not known. Under additional assumptions, such as the monotonicity of Φ as a function of s, one can attempt solutions for the one-dimensional case of a mirroring field. However, the physics of auroral acceleration is often discussed in terms of a "current-voltage relationship (CVR)", linking the field-aligned current density, $J_\parallel$, with the potential drop, $\Delta\Phi$, at altitude s. Various expressions of the CVR have been proposed for different auroral configurations, at microscopic and macroscopic level (for a review see Boström 2003; Pierrard et al. 2007).

As noted by Boström (2003) the effect of orbital dynamics of charged particles in the auroral flux tubes is similar in many ways with the classical plasma physics problem of estimating the flux of electrons between an emitter and a collector in electric discharges (Mott-Smith and Langmuir 1926). Large scale distributed parallel electric fields are formed due to the mutual interaction of ions and electrons moving upward/downward along the auroral flux tube from the magnetospheric (generator) and ionospheric (load) ends. Their orbital motion in the mirroring field leads to corresponding altitude-dependent variations of the phase space density. Various regions of the phase space are populated by particles with different origins and properties, magnetospheric and/or ionospheric. The fundamental dynamics of such particles and the effects on their velocity distribution function and its moments (e.g. $J_{\|}$) is similar in many ways, including the mathematical apparatus, with the dynamics of particles as treated in the exospheric models of polar and solar wind (Lemaire and Scherer 1970, 1971).

The exospheric approach was applied to plasma sheet particle precipitation by Lemaire and Scherer (1973) and Knight (1973) who provided the first expressions for an auroral current-voltage relationship. In this approach the key-issue is the phase space accessibility. Indeed, depending on their kinetic properties at the origin (magnetospheric or ionospheric end of the auroral flux tube) and the local value of the electric and magnetic field, auroral particles can populate only restricted sub-regions of the phase space (see also Whipple 1977; Miller and Khazanov 1993; Liemohn and Khazanov 1998; Khazanov et al. 1998). The moments of the VDF are then obtained from piece-wise integration of the VDF over these sub-regions of the phase space. This approach for solving the Vlasov equation can be effective for a quasi-static quasi-neutral description of auroral particle dynamics and fields. However, it should be noted that these models generally assume a quasi-static potential structure and then determine the distributions that can support it and do not address the development of such a potential structure (e.g., Song and Lysak 2001a, 2001b, 2006).

3.2 Acceleration by Confined, Space-Charge Driven Parallel Electric Fields: Double Layers

Acceleration of downward going auroral electrons can be achieved by small scale electric potential structures that, although globally neutral, have an internal structure organized as two layers of net charges of opposite sign – *a double layer* (*DL*). The existence of double layers is an inherent feature of plasmas, as shown by numerous laboratory experiments (see, e.g., Hershkowitz 1985; Raadu and Rasmussen 1988; Singh et al. 2011). Advocated by Alfven (1986) to have a crucial role in astrophysical particle acceleration, double layers were confirmed as efficient quasi-static auroral accelerations by experimental evidence in spite some theoretical debate (Bryant et al. 1992; Borovsky 1992; see also Eriksson and Boström 1993). Indeed, DLs were detected indirectly for hundreds of FAST orbits (see, e.g., Ergun et al. 2002). The difference with respect to the auroral large scale distributed parallel E-field discussed above is that the double layer introduces a sharp jump of the electric potential (and other plasma parameters) and the parallel electric field is confined within spatial scales of the order of the Debye length.

The origin of these sharp potential structures and fine scale parallel electric fields is at the contact between plasmas with different macroscopic temperatures, ionospheric and magnetospheric, similar to thermoelectric fields in thermodynamics. This similarity was first discussed and described quantitatively in an auroral context by Hultqvist (1971). Experimental evidence from Dynamic Explorer and FAST spacecraft indicates the formation of low-density cavity in the upward field-aligned current region (Persoon et al. 1988; McFadden et al. 1999). FAST data also shows that the low altitude boundary of the auroral cavity, at the contact with the higher density ionospheric plasma, is the site of a strong double layer and a corresponding parallel electric field accelerating downward going electrons (see, e.g., McFadden et al. 1999; Ergun et al. 2002). As argued by McFadden et al. (1999), the formation of the DL may be a consequence of the requirement to maintain quasineutrality on a global scale in the cavity itself that is devoid of cold ionospheric plasma; thus a sharp DL prevents the more energetic secondary ionospheric electrons from entering the cavity.

On the theoretical side, quasi-static double layer solutions are obtained from solving the Vlasov equation together with the Poisson equation:

$$\varepsilon_0 \nabla^2 \Phi = -\left[q_i Q_i^{(000)} + q_e Q_e^{(000)} \right] \tag{6}$$

where the densities are determined as moments of the VDF, as defined by equation (2). The problem of finding stable DL solutions in one spatial dimension is solved by integrating the Vlasov-Poisson system of equations (e.g., Schamel and Bujabarua 1983; Robertson 2014). The solution is described in terms of $V(\Phi)$, the so-called Sagdeev potential, which is equal to within an additive constant to the negative of the total particle pressure (Raadu and Rasmussen 1988):

$$-\frac{1}{2}\varepsilon_0 E^2 + \sum_{i,e} \int_{-\infty}^{\infty} m_{i,e} v^2 f_{i,e}(x, v)\, dv = -\frac{1}{2}\varepsilon_0 E^2 + V(\Phi) = -\Pi \tag{7}$$

where Π is a constant. Two existence conditions must be met by a stable DL: (i) the total particle pressure must be in balance across the DL (*the Langmuir condition*) and (ii) t*he generalized Bohm criterion* stating that, assuming the parallel electric field is zero at the edges of the DL, the net charge on the low and high potential sides are negative and positive, respectively. The latter criterion leads to a condition in terms of velocity distribution functions in close relationship to the dispersion relation for electrostatic waves in a uniform plasma (Raadu and Rasmussen 1988). However, testing of the DL existence criteria with auroral experimental data is difficult and practically never fully achieved.

The conditions for existence of DL solutions in the time independent form are well understood, at least for simplified geometries; however, their stability and therefore the importance for quasi-static acceleration of auroral electrons in the upward field-aligned current region remain questionable. Nevertheless, observations from FAST (Ergun et al. 2002) show evidence that the auroral DL are stable over time intervals of the order of tens of seconds to minutes. Numerical simulations show examples of DL solutions that are stable over time scales compatible with observations of quiet auroral arcs. Vlasov simulations in one and two dimensions (Main et al. 2006) initialized with conditions similar to observations of DL by FAST, show that the DL is stable over time intervals longer than 30000 electron plasma periods, $(\omega_{\mathrm{pe}})^{-1}$, which is tens of seconds assuming typical auroral parameters. These simulations show formation of ion phase space holes at the upper boundary of the cavity but their interaction with the DL does not destabilize its configuration although relatively diminishes its strength. The simulation run is however rather short (of the order of second) compared to real life observations (tens of seconds to minutes). Particle-in-Cell simulations (Main et al. 2010) do confirm the stability of the DL during the entire short time span of the run. As conditions for DL stability the PIC simulations find that the "density of the cold ionospheric electrons to be greater that 30% and the temperature to be less than 100 eV" (Main et al. 2010).

Vlasov simulations provide additional insight compared to PIC. It is shown that the electron acceleration is practically achieved in the double layer itself, when a total potential drop, $\Delta\Phi$, is assumed (Gunell et al. 2013). Nevertheless, a third of the final acceleration energy is gained above the DL; also, the DL altitude decreases with increasing $\Delta\Phi$. Vlasov simulations also confirm that the structure of the accelerating potential is monotonic with the altitude when $\Delta\Phi$ is stable in time but can show local minima/maxima when $\Delta\Phi$ is time dependent (Gunell et al. 2015).

However, the question of how double layers are formed and maintained remains open. The charge separation necessary for a double layer occurs due to the inability of the auroral electrons to carry the current required by the magnetic shear. It has been commonly believed that the non-ideal terms in the parallel components of the generalized Ohm's law, electron inertia, anomalous resistivity, or the electron pressure gradient, inhibit the electron motion and can give rise to parallel electric fields, causing auroral particle acceleration. However it has been pointed out (Song and Lysak 2000, 2001a, 2001b, 2006) that the three non-ideal terms do not describe the generation of parallel electric fields, but simply describe a force balance between the electric force and other forces. An analysis of the full set of Maxwell's equations and Newton's laws indicates that the parallel displacement current, which is often neglected in descriptions of low-frequency phenomena in dense plasmas, is crucial in the generation of parallel electric fields when the plasma density is low (Song and Lysak 2006). As the full Ampere's Law states, when the magnetic shear cannot be balanced by charged particle flow, the displacement current term will lead to an enhancement of the parallel electric field, forming what has been termed an Alfvénic double layer (Song and Lysak 2015).

The generation of a sustained parallel electric field, which requires a sustained energy supply, is associated with the temporal changes and spatial gradients of magnetic and velocity shears. It has been proposed (Song and Lysak 2001a, 2001b) that the nonlinear interaction between incident and reflected Alfven wave packets in the auroral acceleration regions can create local double layers or charge holes. The final state of the interaction of these wave packets can be obtained by considering the approximate conservation of angular momentum and magnetic helicity carried by the two discrete wave packets before and after the collision (Song and Lysak 1994).

It is well known that the reflection coefficient for Alfvén waves interacting with the ionosphere has been given by (Mallinckrodt and Carlson 1978):

$$R = \frac{E_{ref}}{E_{inc}} = \frac{\Sigma_A - \Sigma_P}{\Sigma_A + \Sigma_P} \tag{8}$$

The Pedersen conductance is generally greater than 1 mho while the Alfvén conductance, defined by $\Sigma_A = 1/\mu_0 V_A$, is typically 0.1 mho or less (e.g., Lysak 1990). Therefore, in the usual situation, the reflected wave has a perpendicular electric field in the opposite direction as the incident electric field. In this situation, the incident and reflected wave packets will have the same direction of field-aligned current, and the enhanced magnetic shear in this interaction will lead to an enhancement in the displacement current and the generation of a double layer (Song and Lysak 2001a, 2006). On the other hand, Alfvén waves can also be reflected from strong gradients in the Alfvén speed such as those that exist above the ionosphere. Since the effective conductivity decreases when the Alfvén speed is high, i.e., when the plasma density is low, reflection from the low-density plasma in the acceleration region will produce a reflection with the reflected electric field in the same direction as in the incident electric field. Such reflections will be conducive to the generation of localized electric fields observed as charge holes. Thus, the nonlinear interaction between the incident and reflected Alfvén wave packets in the auroral particle acceleration region can either convert the kinetic energy into electromagnetic energy to generate and support a parallel potential drop, or convert the magnetic energy into kinetic energy to generate a charge condensation (or charge hole), depending on the reflection coefficients. Since upgoing and downgoing shear Alfvén wave packets reflect multiple times from the ionosphere and from Alfvén speed gradients, multiple localized potential drops or charge holes will be generated.

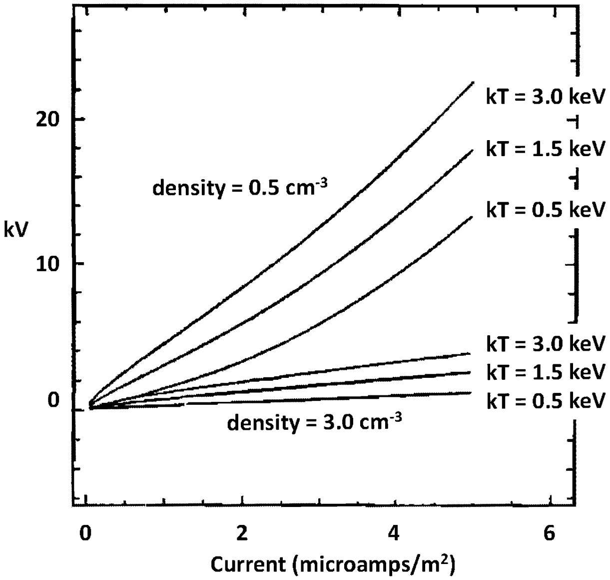


Fig. 2 Current-voltage relation in the downward current region for varying magnetospheric electron density and temperatures for the quasi-neutrality model used by Temerin and Carlson (1998)

4 The Downward Current Region

There are three main observations in the downward, or 'return' current region that need to be addressed by models: acceleration of upward-moving electrons and downward ions, ion conics, and the formation of low-altitude ionospheric densities cavities.

4.1 Particle Acceleration, Parallel Electric Field, and Ion Conics

The existence of both upward accelerated electrons and downward accelerated ions in the return current region indicates acceleration by a downward-directed parallel electric field (Hultqvist 2002), and theories for particle acceleration have concentrated on modelling such a field. One of the first tries (based on earlier work by Stern (1981), and Chiu et al. (1981)) to model the potential drop in the return current region was made by Temerin and Carlson (1998). They invoked quasi-neutrality along a magnetic field line populated by four plasma species; cold ionospheric electrons and ions, and hot magnetospheric electrons and ions. By prescribing an ion density altitude distribution and a field-aligned current, the quasi-neutrality requirement forces an electric field to accelerate the electrons upward in the region above the ionosphere, where the ion density decreases to low values. This results in a current-voltage relation of the return current region, which depends on the density and temperature of the magnetospheric electrons, similar to the Knight relation of the upward current region (see Fig. 2). However, the potential drop in the return current region is typically substantially smaller than the corresponding value in the upward current region for the same value of current density.

Similar models have been developed by Cran-McGreehin and Wright (2005a, 2005b), and Vedin and Rönnmark (2005). Vedin and Rönnmark extended the model to high altitudes and showed that above the maximum of B/n_I, where n_I is the ionospheric electron number density, the electric field changes sign, and points downward. Cran-McGreehin and Wright also attach importance to the B/n peak and argue that the potential drop for a given field-aligned current density is determined by the detailed properties of the ion density profile in the immediate vicinity of that point. It has long been recognized (e.g., Lysak and Hudson 1979) that the peak in the B/n ratio determines the location at which the drift velocity of electrons relative to ions is strongest for a steady-state field-aligned current.

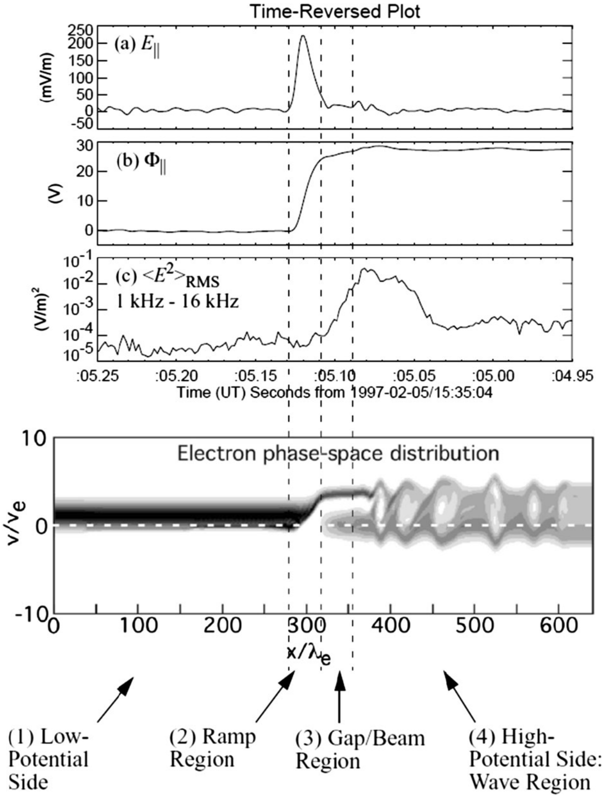
None of the above models takes into account the modification of the ionospheric plasma resulting from the parallel electric field, which is necessary for a self-consistent model of the downward current region. Observations show that the return current region is associated with intense broadband electrostatic low frequency (BBELF) turbulence, heated ions (also in the form of upflowing conics), and a strongly thermalized upward electron beam. These modified plasma populations will affect the solutions to the quasi-neutrality requirement. The exact causal relation between these elements of the downward current region physics are not exactly known and have been modelled in various different ways.

Jasperse (1998), Jasperse and Grossbard (2000), and Jasperse et al. (2010), in a kinetic model (again based on quasi-neutrality) prescribe an ion heating rate due to an ion cyclotron resonance. They assume that BBELF waves exist on the downward current flux tube and are excited by the accelerated electron beam or the field-aligned current without specifying the exact mechanism. The solutions obtained show (in addition to a downward directed electric field) ion distributions identifiable as ion conics. These conics are consistent with the idea of the ‘pressure cooker’ mechanism suggested by Gorney et al. (1985), where the ions are contained at the low-altitude side of the parallel potential drop and are continuously heated until their perpendicular energy is high enough that the mirror force will overcome the potential drop. In this way the ions will escape the ionosphere and under further adiabatic motion will decrease their pitch angle, and form ion beam-like outflows, in spite of the downward-directed electric field.

In the above models, the resulting electric field is smoothly distributed in altitude. Observations indicate that the electric field at times takes the form of double layers, moving upward along the field line at the ion acoustic speed (Andersson et al. 2002). This has been modelled by several authors (Newman et al. 2001, 2008; Liu and Liao 2011; Singh 2003; Singh et al. 2009). Newman et al. (2001, 2008) have used a 1-D Vlasov code to study current driven double layers. A snapshot of the resulting electron phase space is shown in Fig. 3 (which also includes a qualitative comparison to observational data). It can also be seen that the resulting accelerated electron beam is unstable and generates strong electrostatic turbulence, which indicates that the thermalization of the electron beam is a candidate for generating at least a subset of the BBELF waves. Non-linear interaction of the electrostatic turbulence and the ambient plasma can also produce electron phase-space holes, consistent with observations (Goldman et al. 1999, 2007; Ergun et al. 2003; Singh et al. 2009). The idea that the BBELF is located at the high-altitude side of the double layers has also lead to suggestions of an alternative to the pressure-cooker model for the ion heating, involving a self-consistent feedback between the double layer and the heated ion population (Hwang et al. 2008, 2009).

So far, modelling of the downward current region has been focused on the 1-D properties, and the altitude distribution of the parallel electric field. One notable exception is a two-fluid MHD model (Streltsov and Marklund 2006), describing the temporal evolution of the downward current region, where a modification of the ionospheric plasma results in creation of perpendicular, diverging electric fields of the type observed. Similar simulations also show that the ionospheric feedback results in structuring of the downward current region in the perpendicular direction into small-scale current elements or electromagnetic structures (Streltsov and Karlsson 2008; Streltsov and Lotko 2003, 2008). Streltsov (2018) has also addressed the self-consistent formation of narrow, intense regions of downward current, as a consequence of the ionospheric feedback instability (e.g. Atkinson 1970; Sato 1978; Lysak and Song 2002).

Fig. 3 Comparison between observation of a double layer in the downward current region by the FAST spacecraft, and a numerical simulation by Newman et al. (2001). (From Ergun et al. 2003)



The ionospheric modification resulting from the downward currents is further described in the next section.

4.2 Ionospheric Density Cavities

The strong downward current densities in the return current region will result in the creation of a drastic reduction of plasma density when the downward current closes to perpendicular currents in the ionosphere, resulting in a density cavity. This has been modelled in several studies, and it has been shown that the reason for the cavity formation is three-fold.

The first mechanism is an outflow of plasma, resulting from the fact that the field-aligned currents are mainly carried by electrons, due to their high mobility, while the perpendicular Pedersen currents closing the upward and downward currents are mainly carried by ionospheric ions (Doe et al. 1995; Blixt and Brekke 1996). This leads to a net outflow of current carriers in regions where the downward current connects to the perpendicular currents, which can evacuate the main part of the E region plasma in tens of seconds (Doe et al. 1995; Karlsson and Marklund 1998; Karlsson et al. 2005), see Fig. 4.

For the F region, current closure is less efficient in evacuating the ionospheric plasma, and increased recombination due to ohmic heating of the plasma becomes important (Zettergren et al. 2010; Zettergren and Semeter 2012). This process includes temperature-dependent chemical conversion of ionospheric atomic ions to molecular ions, with subsequent fast recombination. At the top-side ionosphere also increased vertical transport becomes important. This transport should perhaps also be taken into account in calculations of the parallel

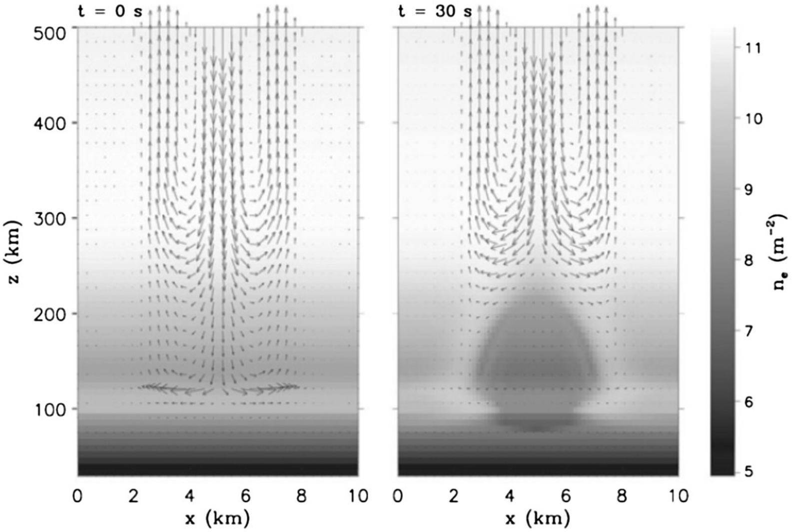


Fig. 4 Ionospheric E-region cavity formation in the downward current region due to an outflow of plasma. (Karlsson et al. 2005)

electric field at higher altitudes. Recent modelling also shows that the resulting cavities can be severely deformed, due to plasma drift and instabilities triggered by the large gradients produced by the cavity formation (Zettergren et al. 2015), or by re-distribution of the currents in the ionosphere (Karlsson and Marklund 1998), or their self-consistent magnetospheric response (Cran-McGreehin et al. 2007).

An important consequence of the cavity formation is the resulting low ionospheric conductivity in that region (Karlsson et al. 2007), which will feed back to the interaction with the magnetosphere. This was mentioned at the end of the previous subsection, and has been further studied by e.g. Russell et al. (2013, 2015). Another suggested consequence is that the large, ohmic parallel electric field formed within the E region cavity can create a suprathermal electron population, which may produce optical emissions similar to those in subauroral red arcs and in sprites (Karlsson et al. 2005). This is a possible mechanism for the phenomenon of enhanced auroral emissions (e.g. Hallinan et al. 1985).

5 Signatures of Alfvénic Acceleration

It was first suggested by Hasegawa (1976) that small perpendicular wavelength Alfvén waves carry a frequency-dependent parallel electric field capable of accelerating electrons to energies sufficient to produce aurora. A fraction of electrons accelerated along the geomagnetic field by these waves will enter the loss cone at a range of altitudes depending on their initial energy and pitch angle, while electrons that cannot overcome the mirror force at low altitudes will form conics as they reverse their direction and move upward along field lines (André and Eliasson 1992). Over the past few decades, numerous observations from rockets (e.g., Arnoldy et al. 1985; McFadden et al. 1986; Lynch et al. 1994, 1999; Semeter et al. 2001) and scientific satellites (e.g., Clemmons et al. 1994; Knudsen et al. 1998; Chaston et al. 2002, 2003a, 2003b) have confirmed this "Alfvénic acceleration" process as viable for producing aurora by elucidating the complex interplay between parallel electric fields, electron conics, and structuring of discrete arcs. While this Alfvénic acceleration process will likely play a role in more dynamic auroral structures (e.g., see the companion article by Kataoka et al. 2020), it can also be associated with field line resonances that have periods of minutes (e.g., Tikhonchuk and Rankin 2000, 2002), and so the resulting auroral structures will appear to be quasi-static. Gillies et al. (2018) have made observations of recurring auroral arcs with periods consistent with field line resonances using a red line (630 nm) imager, which has a response that is dominated by energies < 1 keV; however, they did not measure the electron spectrum directly. As noted above, Alfvén waves also play a major role in the development of quasi-static parallel electric fields, as was suggested in the early work of Lysak and Dum (1983) and in more detail in the work of Vedin and Rönnmark (2006). If the Alfvénic structure is standing in the flow (e.g., Knudsen 1996), the resulting aurora will also appear quasi-static. Such a situation may occur at the plasma sheet boundary layer, where the Alfvénic acceleration may be associated with mode conversion at the Alfvén speed gradients in the boundary layer (e.g., Lysak and Song 2011). Here, we review a subset of observations and theory that summarize the current state of knowledge on the relationship between small scale Alfvén waves and the aurora.

5.1 Two-Fluid Theory

Parallel electric fields are supported by small perpendicular scale Alfvén waves propagating in the inertial or kinetic regime, which depends on the background plasma conditions in which waves propagate. At altitudes of a few Earth radii above the auroral zone, electron pressure gradients support parallel electric fields, with the relevant perpendicular scale being the ion acoustic gyro-radius, $\rho_s = c_s/\Omega_i$, where the ion sound speed and the ion cyclotron frequency are expressed as $c_s = \sqrt{T_e/m_i}$ and $\Omega_i = eB_0/m_i$, respectively, and T_e is the electron temperature in eV. Finite ion Larmor radius effects set a limiting perpendicular scale for waves when $\lambda_e < \rho_s < \rho_i$, where $\rho_i = v_{Ti}/\Omega_i$ is the ion gyro-radius, $v_{Ti} = \sqrt{T_i/m_i}$ is the ion thermal speed, $\lambda_e = c/\omega_{pe}$ is the electron skin depth, and $\omega_{pe} = \sqrt{ne^2/m_e\varepsilon_0}$ is the electron plasma frequency. At scales approaching ρ_i, wave dispersion is altered, but there is no associated contribution to the parallel electric field. When the condition $\lambda_e > \max(\rho_s, \rho_i)$ is satisfied, which is generally true in the auroral acceleration region, the dispersion relation and expression for the parallel electric field are different from the kinetic regime. Within the two-fluid formalism of dispersive Alfvén waves, the parallel electric field, $E_{||}$, in the inertial regime is given by (e.g., Lysak and Song 2005):

$$\frac{E_\parallel}{E_\perp} = -\frac{k_\parallel k_\perp \lambda_e^2}{1 + k_\perp^2 \lambda_e^2} \tag{9}$$

while in the kinetic regime it is given by,

$$\frac{E_\parallel}{E_\perp} = k_\parallel k_\perp \rho_s^2 \tag{10}$$

Both expressions for the parallel electric field assume an infinite homogeneous plasma with the second equation, which is valid for $\lambda_e < \rho_i < \rho_s$, commonly referred to as the kinetic regime. In the above expressions, $E_\perp$ denotes the perpendicular electric field, and $(k_{||}, k_\perp)$ represent parallel and perpendicular wavenumbers, respectively. It is clear that for dispersive Alfvén waves, $E_{||}$ in the inertial and kinetic regimes has opposite sign and that in warm plasma the strength of the field increases in proportion to v_{Te}^2/v_A^2, which can easily reach values on the order of ten in the equatorial plasma sheet. The dependence of the strength of the parallel electric field on increasing plasma temperature with altitude suggests that electron acceleration by dispersive Alfvén waves may be efficient at high altitudes as well as in the "auroral acceleration region." The assessment of this possibility requires a kinetic treatment in which self-consistent Landau damping in hot plasma sheet plasma is accounted for, as is discussed in the next section.

Although two-fluid theory excludes Landau damping effects, it has nevertheless aided the interpretation of distribution functions modified by dispersive Alfvén waves. In particular, because direct measurements of $E_{||}$ are not generally available, observations of wave perpendicular fields are used along with the two-fluid dispersion relation to provide evidence of electron acceleration by $E_{||}$ (Wygant et al. 2002). Test particle simulations and linear wave two-fluid theory successfully also reproduces observations of electron energy-time dispersion expected of small scale Alfvén waves (Thompson and Lysak 1996; Chaston et al. 2002). Nonlinear theory of two-fluid dispersive Alfvén waves has been developed to explain observations attributed to colliding wave packets (Song and Lysak 2001a, 2001b, 2006), ponderomotive effects (Sydorenko et al. 2008), and the formation of kinetic Alfvén wave solitons (e.g., Wu et al. 1995).

In homogeneous plasma, the inertial and kinetic regimes of Alfvén wave propagation do not overlap. Some studies have combined the two-fluid inertial and kinetic regimes by merely adding expressions for the parallel electric field for the inertial and kinetic regimes. The motivation for this is that Alfvén waves propagating along geomagnetic field lines naturally transition from the kinetic regime at high altitude to the inertial regime at low altitude (e.g., Lysak and Carlson 1981). However, there is no formal justification for combining the two limits of the dispersion relation, which is in any case easily avoided by solving the full kinetic dispersion relation (Lysak and Lotko 1996). On geomagnetic field lines with changing density, temperature, and magnetic field strength the kinetic dispersion relation can be used to describe the characteristics of propagating Alfvén waves provided the parallel wavelength is smaller than the characteristic length scale of variation of field line plasma parameters.

Two-fluid theory reveals that at a certain altitude the parallel electric field of a propagating or standing two-fluid dispersive Alfvén wave changes sign at a location where counteracting effects of inertial and kinetic wave dispersion are in balance. The transition from one regime to the other has important implications for standing Alfvén waves, which can become trapped on geomagnetic field lines into a narrow range of L-shell (Streltsov and Lotko 1995) with little or no losses, except at the ionospheres. In a driven system under these circumstances, phase mixing on auroral field lines will lead to a spatial structure consistent with a discrete arc, i.e., a field-aligned current system confined to a very narrow range of latitude, and with a correspondingly strong parallel electric field (Lysak and Song 2008, 2011). For dispersive standing Alfvén waves, this focusing effect leads naturally to a concentration of wave energy and parallel electric fields on geomagnetic field lines where this minimum perpendicular wavelength occurs.

5.2 Kinetic Dispersion and Simulations

Theoretical and numerical studies on field-aligned electron acceleration processes by the Alfvén waves have largely been advanced in the last two decades. The kinetic dispersion relation incorporating ρ_s and λ_e effects can be derived following (Nakamura 2000) and is written for a Lorentzian distribution function,

$$\frac{E_{\|}}{E_{\perp}} = \frac{v_{T\kappa}^2}{V_A^2} k_{\|} k_{\perp} \lambda_e^2 \frac{1}{2\left[1 - 1/2\kappa + \zeta Z_{\kappa}(\zeta)\right]} \tag{11}$$

where $v_{T\kappa} = [2\kappa - 3]^{1/2} v_{Th}$ is an effective thermal speed of electrons, κ is the so-called "Kappa" parameter, $\zeta = \omega / k_{\|} v_{T\kappa}$, and $Z_\kappa(\zeta)$ is the modified dispersion function introduced by Summers and Thorne (1992). For large values of κ the expression for $E_{||}$ obtained from the kinetic dispersion relation has cold and warm plasma limits corresponding to the inertial and kinetic regimes described earlier. However, in addition to these effects, Landau damping is included in the kinetic description associated with the imaginary part of the dispersion function. There have been several studies to assess the consequences of the kinetic regime of electron acceleration including the Landau damping (Damiano et al. 2007; Seyler and Liu 2007; Swift 2007; Watt and Rankin 2009; Lysak and Song 2011). Interactions of kinetic Alfvén waves and field-aligned electron motions have been investigated by means of the one-dimensional drift kinetic model (see, for example, Watt et al. 2004; Watt and Rankin 2009) or by use of the particle-in-cell (Clark and Seyler 1999; Seyler and Liu 2007) or a hybrid-MHD simulations (Damiano et al. 2003; Damiano and Wright 2005).

The effect of electron trapping in kinetic Alfvén waves has also been considered (Watt and Rankin 2009, 2010, 2012; Damiano et al. 2015, 2016). This trapping mechanism is much more efficient than the electrostatic mechanism considered by Damiano et al. (2016) and is supported by Vlasov-kinetic simulations (Watt and Rankin 2009). Watt and Rankin (2010) have shown that this mechanism can accelerate electrons to the 1-10 keV range with sufficient energy flux to power discrete auroral emissions. Their simulations considered waves that had a characteristic period of 2 seconds and a wavelength mapped to the ionosphere of 4 km. Damiano et al. (2015) found that ion temperature effects reduce parallel currents and electron energization all along geomagnetic field lines as expected for a kinetic Alfvén wave. In a subsequent study by the same authors (Damiano et al. 2016) it was found that as the ion temperature increases the ability of kinetic Alfvén waves to carry and energize trapped electrons is reduced by more significant wave energy dispersion perpendicular to the ambient magnetic field. However, the trapping mechanism evaluated by these authors differs from the mechanism considered by Artemyev et al. (2015), which can be realized only in a system with magnetic field inhomogeneity. In this case, an effective potential well into which electrons become trapped is generated by the wave parallel electric field and mirror force.

The local dispersion relation used in all of these kinetic theories is strictly valid in infinite homogeneous plasma. When long-period field line resonances (FLRs) reach latitude widths at which dispersive effects are important, the electron transit time along geomagnetic field lines has to be considered. The latter can be much shorter than a typical FLR wave period, in which case Ohm's law breaks down. A non-local theory of the interaction of auroral electrons that accounts for electron bounce motion has been developed by Rankin et al. (1999) and Tikhonchuk and Rankin (2000) and exhibits enhanced parallel electric fields in FLRs. More detail on these types of interaction in FLRs and the limitations of two-fluid and local kinetic theories are given in the companion paper by Rankin et al. (2020). A final aspect of Alfvénic acceleration of auroral electrons is formulated in terms of the feedback magnetosphere-ionosphere (M-I) coupling, which has long been considered to be a mechanism for quiet auroral arcs (Atkinson 1970; Sato 1978). These studies consider the ionization produced by particle precipitation, which can cause conductivity gradients that can give rise to kinetic Alfvén waves when the phase relations between up and down going waves is favorable (Miura and Sato 1980; Lysak 1991). Such feedback can occur due to reflections in the conjugate ionosphere, in which case the resulting structures are slowly evolving on time scales of minutes, or by reflections in the ionospheric Alfvén resonator (e.g., Lysak and Song 2002; Streltsov and Lotko 2008). A feedback model where the kinetic Alfvén waves are described by means of the gyrokinetic equations, are amplified through the M-I interactions, and accelerate electrons self-consistently based on reflections from the conjugate ionosphere has been presented (Watanabe 2014). On the other hand, Sydorenko and Rankin (2017) have questioned the existence of this instability; however, this conclusion has been challenged by Streltsov and Mishin (2018). Thus, this question remains open.

6 Observations of Auroral Acceleration and of the Auroral Acceleration Region

Following the suggestion by Alfvén (1958), that (quasi)static parallel electric fields / double layers could develop on auroral field lines and decouple the ionospheric from the magnetospheric plasma motion, a broad range of signatures was observed, supporting Alfvén's early intuition. As described earlier in this chapter, rocket experiments in the 1960's showed monoenergetic peaks in the electron data, indicative for acceleration by a quasi-static potential drop along the magnetic field line, while later on, the inverted-V signature was discovered in electron spectrograms from the Injun-5 satellite. Gurnett (1972a, 1972b) found that inverted-V signatures were associated with electric field reversals and interpreted this observation in terms of a 'U' (or 'V') shaped of the electron acceleration region (Fig. 5, top left). A similar conclusion was reached independently by Carlqvist and Boström (1970), based on high speed (well above typical ionospheric speeds) counter-streaming flows at the arc boundaries, observed by a low luminosity TV camera.

The discovery "almost by chance" (according to Fälthammar 1983), of the auroral acceleration region (AAR) by the S3-3 satellite, confirmed the suggestion of Gurnett (1972a, 1972b), and was based on systematic observations of specific features such as electrostatic shocks (Mozer et al. 1977), ion beams (Shelley et al. 1976; Ghielmetti et al. 1978) and ion conics (Sharp et al. 1977; Gorney et al. 1981). Signatures of the ion and electron phase space consistent with quasi-static acceleration by parallel electric fields (Mizera and Fennell 1977), as well as double layers and solitary waves (Temerin et al. 1982), were also observed by S3-3. Comprehensive reviews of the S3-3 discoveries and investigations were provided e.g. by Mozer et al. (1980) and Chiu et al. (1983). Figure 5 shows an updated perspective of the AAR as derived from S3-3 observations (Mizera et al. 1982).

After S3-3, several spacecraft missions on polar or near polar orbits explored the AAR with progressively better resolution and accuracy, among them Dynamics Explorer (DE), Viking, Akebono, Freja, Interball-Aurora, and Polar. The DE mission, consisting of two satellites at high and low altitude (DE-1, apogee at $\sim$23000 km, and DE-2, apogee at $\sim$1000 km), was designed to provide repeated conjunctions between the two spacecraft, which enabled Reiff et al. (1988) to perform consistent comparisons of the field-aligned potential drop inferred by DE-1 (electron and ion data) and DE-2 (electron data).

A comprehensive investigation of the AAR was made possible by the Fast Auroral SnapshoT (FAST) mission (1996–2009, apogee at 4100 km, see Carlson et al. 1998a), whose orbit and high resolution payload turned out to be optimal to explore both quasi-static and transient features of the auroral acceleration. By showing systematically that the integral of the electric field along the satellite path is essentially equal to the average energy of the beam ions (McFadden et al. 1998), FAST provided strong evidence for the electrostatic character of the auroral acceleration in the upward current region. A similar relationship was found in the downward current region, this time between the integral and of the electric field and the average energy of the beam electrons (Carlson et al. 1998b), providing systematic support

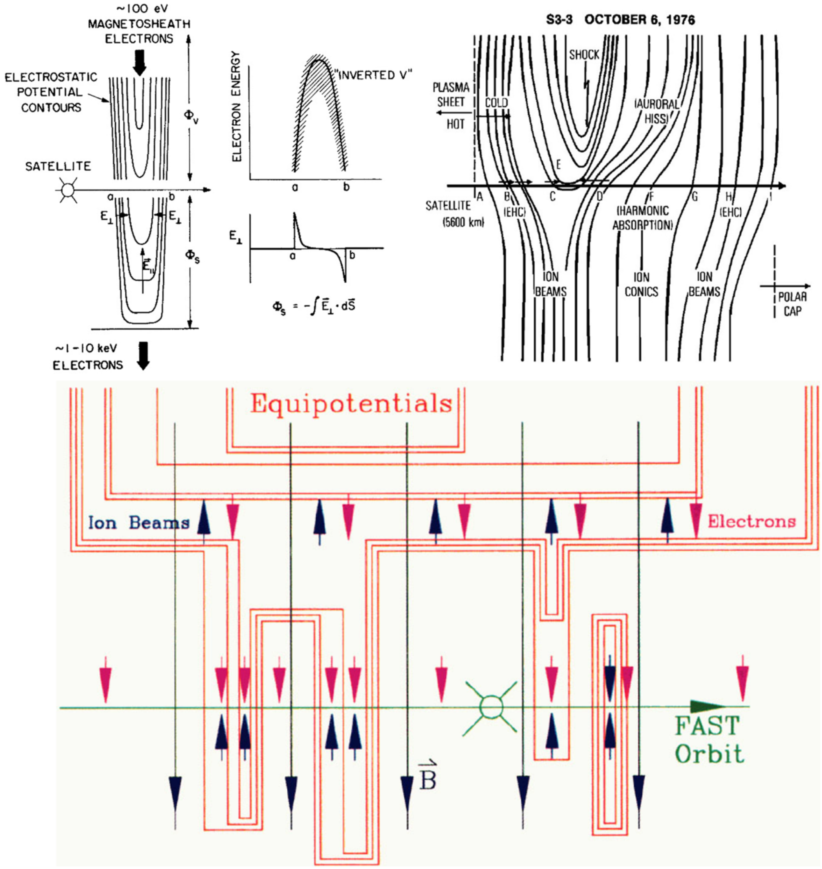


Fig. 5 The configuration of the auroral acceleration region as inferred from Injun-5 (Gurnett 1972b, top left), S3-3 (Mizera et al. 1982, top right), and FAST (McFadden et al. 1999, bottom) data

for quasi-static acceleration over 'black aurora', first observed in the Freja data by Marklund et al. (1994).

A summary of AAR FAST findings was provided by McFadden et al. (1999). Figure 5 (bottom) shows a sketch of the FAST perspective on the AAR structure in the upward current region. Subsequently, a broad range of FAST observations was used to illustrate various AAR features in the ISSI monograph on Auroral Plasma Physics (Eds. Paschmann et al. 2003), in particular in Chap. 4.

With less payload but a high resolution narrow angle camera, actively pointed to the ionospheric footprint of the magnetic field line, the Reimei satellite (launched in 2005), in an almost circular orbit at ~650 km (see Saito et al. 2005), was able to complement FAST data and provide insight into the relationship between quasi-static and Alfvénic acceleration, e.g. in the case of an onset arc (Frey et al. 2010). Reimei data were particularly useful to advance the understanding of highly dynamic aurora, whose small scale structuring was found to be driven by Alfvénic turbulence cascade (Chaston et al. 2011).

Until the launch of the four-spacecraft Cluster mission in July-August 2000, the AAR was explored mainly by single spacecraft missions, with the notable exception of DE, providing conjugacy along the magnetic field between the low and high altitude satellite, as well as of Polar and Reimei, equipped with cameras able to take auroral images conjugate to the in-situ observations. However, until Cluster, no mission was able to separate unequivocally temporal from spatial variations and, consequently, to investigate the AAR evolution in time. One early example for this capability of Cluster was provided by an event study of the divergent electric field evolution in time (Marklund et al. 2001a, 2001b). Later on, when the gradual change in orbit due to moon influence resulted in frequent Cluster crossings of the AAR topside, several studies explored both the altitudinal distribution of the Cluster potential and its development in time (e.g. Marklund et al. 2001a, 2001b, 2012; Sadeghi et al. 2011). More details on Cluster observations are available in the previous article in this collection (Karlsson et al. 2020), as well as, e.g., in the AAR review by Karlsson (2012).

As mentioned earlier, an important feature of the field-aligned potential drop is the so-called current-voltage relationship (Knight 1973), based on energy conservation and on the adiabatic particle motion in a converging magnetic field. Irrespective of the altitudinal distribution of the electric potential (subject to conditions of accessibility, see, e.g., Boström 2003, 2004), the current density can be shown to vary linearly with the field-aligned potential drop, for a broad range of potential drops typical of the AAR. This relationship, which is particularly important for including the AAR in M–I coupling models, was first verified by rocket data (Lundin and Sandahl 1978; Lyons et al. 1979) and later on by satellite data, e.g. Weimer et al. (1985, 1987) and Lu et al. (1991) based on DE data, Sakanoi et al. (1995) based on Akebono data, Frey et al. (1998) and Olsson et al. (1998) based on Freja data, and Elphic et al. (1998) based on FAST data.

Finally, the altitudinal distribution of the potential drop and the altitudes of the lower and upper AAR boundaries were investigated by various statistical and event-oriented approaches. An overview of statistical results was provided by Karlsson (2012), completed, in the meanwhile, by a Cluster based investigation (Alm et al. 2015a). Among the event oriented techniques, Marghitu et al. (2006) and Forsyth et al. (2012) used the anisotropy of the observed electron distributions to infer the altitude of the upper AAR boundary, while more recently, Hatch et al. (2019) estimated the same altitude by fitting moment-voltage relationships parameters (including magnetic field ratio) over a range of different voltages. Detailed features of the electron distribution function can be used as well, e.g. to find properties of concentrated electric fields / double layers located above the satellite (Vedin et al. 2007). Naturally, multi-point observations provide better constraints to the altitudinal distribution of the electric potential, as shown by Cluster events (e.g. Sadeghi et al. 2011; Alm et al. 2015b).

7 Summary and Conclusions

While a great deal of progress has been made on the theory of quiet, discrete arcs, a number of important questions remain. One issue involves the predicted scale sizes of arcs. As noted in the previous chapter (Karlsson et al. 2020) observed scale sizes appear to have a rather continuous spectrum from less than 100 m up to about 100 km (Maggs and Davis 1968; Knudsen et al. 2001; Partamies et al. 2010). The larger scale size is consistent with estimates based on the Knight relation and current closure through the ionosphere (Lyons 1980), while smaller scale sizes may be associated with the electron inertial length in the acceleration region (e.g., Goertz and Boswell 1979), typically a few kilometers. Ionospheric feedback tends to produce very small scale structures, which are likely limited by the effect of collisional resistivity in the ionosphere (Forget et al. 1991; Lessard and Knudsen 2001), which can give scales of less than a kilometer (Lysak and Song 2002). It may be the case that these smaller-scale structures are mostly associated with dynamic arcs rather than the quiet arcs that are the main focus here. However, the rather continuous spectrum in scale sizes raises the question of whether the underlying dynamics is much different for quiet and more dynamic arcs.

Predicted time scales for auroral arcs also constitute a broad spectrum. Of course, the steady-state models described in Sect. 2 above assume that the system is not evolving, and so can shed little information about time scales. As noted above, double layer simulations have produced stable structures over the length of the runs, with periods of up to tens of seconds. It is not clear how long a double layer could ultimately exist if the simulations were carried out to larger times. Multi-spacecraft investigations of how a quasi-static acceleration region develops, similar to observations from the Cluster mission (Marklund et al. 2001a, 2001b, 2012), are also needed in the future to establish this process. It should also be noted that the time scale of quiet discrete arcs may also be determined by the generation mechanism. Potential generator mechanisms are discussed in the companion paper by Borovsky et al. (2020).

One clear distinction in time scales can be seen in the distinction between monoenergetic and broadband electron acceleration. Broadband acceleration would be favored if the transit time of electrons through the acceleration region, time scale of a few seconds for an acceleration region the order of 1 R_E in length, is longer than the time scale of the evolution. Thus, Alfvénic acceleration in the ionospheric Alfvén resonator would produce a broadband spectrum of electron energies, while a similar acceleration process in a field line resonance that has a period of a few minutes would give a more monoenergetic spectrum that would be stable over this time scale.

A final question is how the energy of the accelerated electrons depends on the acceleration mechanism. Observations generally show that monoenergetic electrons generally have energies above 1 keV, while broadband electrons are often of lower energies. However, test particle models and observations of auroral acceleration (e.g., Chaston et al. 2002, 2003a, 2003b) show that inertial Alfvén waves can produce broadband acceleration up to 10 keV, although typical energies are 1 keV or less. Thus, while quiet arcs are generally associated with monoenergetic electrons, it is possible that in some cases they may be produced by a broadband electron distribution.

Further observations, combined with relevant theory, could shed new light on these structures. For example, simultaneous observations at different altitudes along the field line could address the question of whether the parallel electric fields are distributed over large distances, as was discussed above in Sect. 3A, or if they are concentrated in double layers as in Sect. 3B. Further studies relating observed auroral arcs with electron precipitation, like those from the Reimei satellite (Chaston et al. 2011; Fukuda et al. 2014) would help establish what types of particle acceleration are associated with different auroral emissions. In addition, studies such as those from the Swarm and ePOP missions (e.g., Miles et al. 2018; Pakhotin et al. 2018) that combine observations with model results can address the structure of electric and magnetic fields in the auroral region.

Therefore, despite the fact that the basic ingredients of auroral acceleration processes are reasonably well understood, many questions as to how these ingredients work together remain to be answered. Hopefully, future missions, likely with multiple point measurements, will be planned to investigate the remaining issues in auroral acceleration processes.

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