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Formation of the small-scale structure of auroral electron precipitations

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ABSTRACT

This paper is aimed at physical causes of the small-scale transverse structure in the flows of auroral electrons, generating the corresponding small-scale structure of discrete auroras. The parallel electric field existing in the lower part of the auroral magnetosphere, in the auroral cavity region, in the presence of a strong upward field-aligned current, accelerates magnetospheric electrons to energies of ~1 – 10 keV. The flow of these particles while maintaining the high density of the field-aligned current, produces a current-driven instability, which generates Alfvénic turbulence at short perpendicular wavelengths ≤ 1 km. These short-wavelength inertial Alfvén disturbances possess a nonzero parallell electric field, which modulates the electron flow velocity. The modulation occurring at high altitudes $\geq 10^4$ km leads to a nonlinear effect of formation of strong density peaks at low altitudes of electron precipitation. The transverse, horizontal scales of the corresponding electron flow structure coincide with the small scales of the Alfvénic turbulence; and this structuring leads to non-uniformities in the auroral luminosity on the same scales, i.e., to small-scale structure of discrete auroras.

1. Introduction

After decades of intense research, plasma dynamics of the auroral region is still one of the most difficult and interesting problems in the physics of the magnetosphere. Of course, there is already a number of well-founded ideas, based on the results of satellite and ground-based measurements. During the last two decades, in a number of excellent experiments, a large amount of data was collected (e.g., Paschmann et al., 2003; McFadden et al., 1999a, 1999b; Chaston and Seki, 2010; Chaston et al., 2010, 2011; Ergun et al., 2000), concerning the particle and fields environment in the auroral upper ionosphere – lower magnetosphere region. As the authors of publications point out, those results basically confirmed the general concepts established earlier and mainly concerning the large-scale structure of the auroral plasma system. In the disturbed magnetosphere, field-aligned flows of energetic electrons precipitating from the magnetosphere, with energies ~1 – 10 keV, form "inverted-V" structures in the latitudinal direction: electrons of the quasi-monoenergetic flow have the maximum energy at the central latitude, with decrease of energy at higher and lower latitudes. The latitudinal scale of such a structure is of the order of hundreds of kilometers. The electron flows in the "inverted-V's" carry a field-aligned current of high density: those are the most powerful field-aligned currents involved in the three-dimensional current system of the disturbed magnetosphere.

However the experiments mentioned above, were mostly aimed at the further study of the auroral physics in detail, in the wider spatial range and on the fine spatial and temporal scale. Correspondingly, for their interpretation a number of more or less sophisticated models were proposed. In many of them much resemblance of results was achieved in relation to the observational data concerning the structuring of electric and magnetic fields, of particle distribution functions, and of auroral forms.

In particular, auroral observations show that a the heights of the glow, ~100 km, the flows of energetic electrons that generate auroras, are highly horizontally structured: they generate small-scale structure of discrete auroras, whose horizontal scales range from a few kilometers to tens of meters (Borovsky, 1993; Sandahl et al., 2008; Kozelov and Golovchanskaya, 2010).

An important feature of discrete auroral forms is that their spatial spectrum is close to that of transverse scales of simultaneously observed Alfvénic turbulence (Stasiewicz et al., 2000a; Golovchanskaya et al., 2011). Such electromagnetic wave turbulence is observed aboard spacecraft in the auroral region above the auroras, in the upper ionosphere - lower magnetosphere region, at altitudes $\geq 10^3$ km (Gurnett et al., 1984; Lindqvist and Marklund, 1990; Stasiewicz et al., 2000a; Ergun et al., 1998). At relatively high frequencies (in the satellite frame) corresponding to large transverse wave numbers, the Alfvénic disturbances are actually inertial Alfvén waves (Goertz, 1984; Stasiewicz et al., 2000b). They have a

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nonzero magnetic-field-aligned component of the electric field, so that they interact effectively with parallel electron flows.

The origin of large-amplitude small-scale Alfvén waves in the regions occupied by auroral field-aligned currents is a matter of many recent studies. One of the most promising approaches is the premise that such waves might be produced by self-consistent magnetosphere-ionosphere (M-I) coupling (Streltsov and Lotko, 2004; Streltsov and Karlsson, 2008; Russell et al., 2013). Numerical experiments have demonstrated that waves resembling observations are produced by a simulated system's response to large-scale field-aligned currents via the ionospheric feedback mechanism (IFM).

While this mechanism may really be responsible for generation of large-amplitude small-scale Alfvén waves and associated current structuring in the auroral upper ionosphere –lower magnetosphere region, we propose in this paper that those small-scale inertial Alfvén waves which are eventually responsible for the strong structuring of energetic auroral electrons, should be generated by current-driven instability *above* that region, in the very low-beta plasma typical for auroral cavity environment (Chen et al., 2013) where the strong field-aligned current is carried by electrons accelerated at even higher altitudes.

Another approach to the problem was proposed in the paper (Chaston and Seki, 2010). The modeling there is based on the equations of the single-fluid MHD theory for a plasma with a field-aligned current initially distributed smoothly over a large transverse scale. A uniform magnetic field is assumed, so that the influence of magnetic mirroring is excluded in principle. In such a model evolution occurs, leading to transverse structuring of the field-aligned current, based on Alfvénic turbulence, and correspondingly, of the vertical energy flux.

However, although there is similarity of these structures with the observed auroral forms (Chaston et al., 2010, 2011), the real physics might be different. In fact, in “inverted-V” regions with very intense upward field-aligned current, the small-scale precipitation patterns are generated specifically by the structured quasi-monoenergetic electron beams. The plasma model must fundamentally be kinetic: the electron distribution function is a beam (coming from outside) on the cold isotropic background. Evolution of such a system with a beam is described by equations different from the hydrodynamic equation set adopted in the paper (Chaston and Seki, 2010).

Of course, in such a fluid model there also exists a possibility of nonlinear evolution processes in the plasma of the auroral upper ionosphere - lower magnetosphere, resulting in transverse structuring which is just shown in (Chaston and Seki, 2010). However, in our opinion, in the first place attention should be paid to the nonlinear process of that strong structuring at low altitudes, which is initiated by weak variations of an initially wide electron flow earlier accelerated at higher altitudes, where it should basically be formed in order to provide a strong field-aligned current observed in “inverted V's”.

We would like to emphasize here an associated fundamental issue which, in our opinion, has not been paid enough attention in those recent studies. It was pointed out back in the 80-ties that during geomagnetically disturbed times, very strong upward field-aligned currents are involved in the three-dimensional magnetosphere-ionosphere current system (“substorm current wedge”). Such a current cannot be maintained by the upward ion flow from the ionosphere: it proves to be insufficient. It follows that the current should be carried by magnetospheric electrons. However in normal conditions, even with the loss cone totally filled-up, the flow of hot magnetospheric electrons is also insufficient (see e.g. Kivelson and Russell, 1995). To improve the situation, the loss cone must be widened. And this is only possible if an electric field appears along the magnetic field lines, accelerating electrons down the field lines. Importantly, the localized potential drops appearing in the region of upper ionosphere – lower magnetosphere, which have been often included in simulations, actually cannot serve the aim. Since the electrons, in their bounce motion, are mirroring in the converging magnetic field, the sufficient number of electrons can only be collected at higher altitudes, by means of the loss cone widening over there.

The presence of parallel electric fields in the inertial Alfvén waves has led some researchers to seek a direct causal link between the waves and the flow of auroral electrons in the belief that their acceleration up to 1–10 keV can occur under the action of parallel fields of the inertial Alfvén waves (e.g., Thompson and Lysak, 1996; Lysak, 1998; Lysak and Song, 2003; Wu and Chao, 2004). We do not generally deny such a possibility. But (1) it certainly may be that those inertial Alfvén waves which demonstrate similarity of the spectra to those of auroral forms are not those waves which are thought to be responsible for electron acceleration: mesoscale mechanisms that ensure a significant fraction of the auroral acceleration are separated from the small-scale acceleration, due to dispersive Alfvén waves, which contribute to the transverse wave structuring similar to precipitation structuring; (2) we believe that generally the waves play a key role not in the basic mechanism of electron acceleration up to the auroral energies but in the mechanism of the horizontal structuring which is observed at low altitudes where the auroral luminescence is excited.

As to the basic mechanism of electron acceleration, it was pointed out a long time ago that the electric potential drop distributed along the magnetic field line, provides acceleration of magnetospheric electrons down toward the ionosphere. The flows of accelerated electrons are really observed in the auroral upper atmosphere as the well-known “inverted V” structures. These electrons form quasi-monoenergetic beams there. It has been shown that the current density $j_I \simeq e n_{eI} v_I$ is nearly proportional to the overall potential drop U, from ionosphere to the equator (n_{eI} and v_I are the electron number density and parallel velocity, respectively, at the ionospheric level), (Knight, 1973). This result is known as the “effective Ohm's law” $j_I \simeq -KU$; $K = \frac{n_M e^2}{\sqrt{2\pi m T_M}}$ with the subscript M relating to the magnetospheric equatorial region.

However, this is only an approximate relation, with a limited range of validity; a number of refinements have been later proposed (Antonova and Tverskoy, 1975; Whipple, 1977; Chiu and Schulz, 1978; Stern, 1981). Note also that basically this is a kinetic effect, it appears in the collisionless kinetic theory. If we turn to the fluid theory as e.g. in (Chaston and Seki, 2010), there is no reason to build up a finite conductivity and related diffusion of the magnetic field on this basis. True, the particle distributions which arise, may prove to be unstable relative to plasma waves generation, and this can lead to plasma wave turbulence and associated anomalous resistivity, but this is another story. There is a number of papers where such effects, being localized and not global over a field line, have been analyzed (e.g., Lysak and Dum, 1983; Lysak, 1990). And this approach might also be quite fruitful in understanding the electromagnetic structures in the upper ionosphere – lower magnetosphere. Anyway we believe that the structuring which arises as a result of those corresponding simulations, should be looked at as complimentary to the effect analyzed in this paper, at least for situations with the strongest upward field-aligned currents as pointed out above.

In our approach, we turn to the real physical nature of the large-scale distributed potential drop itself. That nature was identified in a series of papers (Kropotkin and Martyanov, 1985, 1989; Kropotkin, 1985, 1986). It was done along the following lines. (1) The mechanism of charge separation acting in the near-equatorial region and forming the substorm current wedge, thus