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Auroral Potential Structures and Current-Voltage Relationship: Summary of Recent Results

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Abstract. Discrete auroral arcs are caused by precipitating accelerated electrons, and there is a lot of observational evidence for the associated potential structure being U-shaped below about 15000 km altitude. However, according to our studies using Polar data at higher altitude, there is a lack of convergent electric field signatures at ~20000-35000 km and consequently we suggest that the U-shaped potential contours close below this altitude range. To explain this finding, an O-shaped potential model is proposed, together with a maintenance mechanism which involves parallel energisation of middle-energy electrons by waves in the 15000-30000 km altitude range. Test particle simulations show that the presence of waves brings this "cooperative" model in quantitative agreement with both Polar and low-altitude observations. We also discuss our statistical Freja satellite studies of the observational relationship between the peak energy (voltage) and the current density in inverted-V regions. The result is that the current and voltage are sometimes correlated in the evening sector events, but almost always anticorrelated in the morning sector. This result, which is very interesting in its own right, may also have some relationship to the potential structure question.

1 Introduction

It is known that discrete auroral arcs are caused by precipitating magnetospheric electrons, which are accelerated somewhere above the ionosphere in such a way that their energy spectrum has a distinctive peak usually at several keV energy (e.g., Lin and Hoffman, 1979; Bryant, 1999). If one passes through a simple discrete auroral arc in the transverse direction with a sounding rocket or a low-orbiting satellite, the peak energy increases and then decreases, generally reaching a maximum value near the center of the arc. For this reason, the spectra causing discrete arcs are usually said to have an "inverted-V" form.

The inverted-V electrons are accelerated in the acceleration region at about 6000-13000 km altitude. There is a lot of evidence that an upward parallel electric field is responsible for the inverted-V electron acceleration (Evans, 1974). It is also known from satellites that pass through the acceleration region that intense perpendicular electric fields exist in this altitude range (Mozer *et al.*, 1980). Furthermore, the nature of the perpendicular electric field is such that if one forms the line integral of the perpendicular field along the satellite orbit, one obtains a potential value which is generally in agreement with the energy of upward accelerated ion beams (in converging electric field regions) or electron beams (in diverging horizontal electric field regions) observed simultaneously by the particle detectors of the satellite (Marklund, 1993; McFadden *et al.*, 1998). This has given rise to the theory that the DC electric field is mainly a potential field at this altitude, and the potential contours are U-shaped, the bottom of the "U" corresponding to the upward parallel electric field (Carlqvist and Boström, 1970).

Often there are optical undulations or waves moving eastward and westward along the equatorward and poleward edges of an arc (Davis, 1978; Haerendel *et al.*, 1996). They have been interpreted as reflecting the $\mathbf{E} \times \mathbf{B}$ velocity at and above the acceleration region. The speed of these structures approximately matches the strength of the arc-associated convergent perpendicular fields estimated from the potential drop and the width of the arc, which is another evidence for the applicability of the U-shaped potential picture below about 15000 km altitude (Haerendel *et al.*, 1996; Janhunen *et al.*, 1999b).

This paper, with its limited space, attempts to summarise our recent results concerning auroral potential structures and the current-voltage (CV) relationship. Most of the results are being published in much more detail elsewhere. The paper can therefore be thought of as a "snapshot" of our ongoing work. In this work the methods and instruments vary, but the main aim is to understand the physical processes that are responsible for the creation and maintenance of discrete auroral arcs and inverted-V spectra. The research is motivated by the fact that despite about 30 years of intensive oberva-

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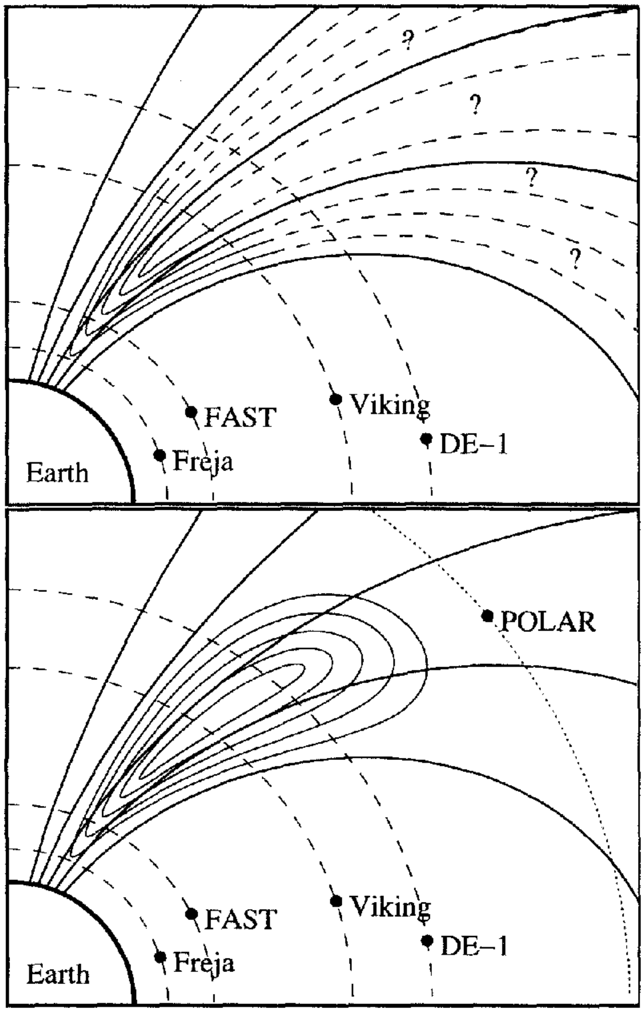

Fig. 1. *Top:* The knowledge of the acceleration region before POLAR satellite results (Janhunen *et al.*, 1999a). The potential structure above 15000 km was poorly known from measurements, but was generally assumed to follow the dashed potential contours. The latitudinal width of the potential structure is exaggerated in order to ease visualisation. *Bottom:* The postulated O-shaped potential explanation for the observed (Janhunen *et al.*, 1999a) lack of convergent electric field structures at POLAR altitude.

tional studies, the basic questions about auroral arcs are still open. For example, why arcs are long and narrow, what determines where and when they form, how wide they are and what the peak energy is.

2 Relative absence of electric field above 25000 km

There are lots of *in situ* satellite observations of the auroral region below about 13000 km altitude, some around 15000 km (Reiff *et al.*, 1988), but much fewer higher up, except far in the magnetosphere and close to the equatorial plane. The Polar satellite intersects the northern auroral oval at about 25000-35000 km altitude, depending on the orbit, and thus can give us valuable information in this poorly known altitude range. Consequently, we studied Polar electric field data using 87 orbits where simultaneous ground-based magnetic observations were also available (Janhunen *et al.*, 1999a). The idea was to study whether the upright "legs" of the U-shaped potentials can be seen in this altitude range (Figure 1). The result was rather surprising: There was an almost complete lack of evidence for the convergent electric field structures in this altitude range. In a few events, weak (1-2 kV) potential wells could be seen, but even they could have been caused by temporal variations. To check that this result was not due to some data processing error, we took a number of Polar southern hemisphere passes (about 6000-10000 km altitude range, i.e. in the acceleration region) and found many examples of convergent electric fields corresponding to several kV potential minima, using the same analysis method as for the northern hemisphere passes. To explain the observations, we postulated that the potential contours close below Polar altitude, i.e. that they are O-shaped rather than U-shaped (Figure 1). Finding the potential by integrating along the satellite orbit gives a correct result only in a stationary situation. Therefore substorm-related cases were eliminated in the Polar study, and the conclusions concern only stable arcs. Our conclusions *might* also apply to dynamically varying arcs, but we cannot verify it from the Polar electric field observations.

Notice that the lower part of an O-shaped potential is U-shaped. Thus the phrase "O-shaped potential" should not be viewed as the opposite of the "U-shaped potential", but rather as a way of completing the U-shaped potential contours. The O-shaped potential model is, however, markedly different from a model in which the field lines are equipotentials above the acceleration region and the U-shaped contours continue all the way to the equatorial plane, closing only in the opposite hemisphere in a (presumably symmetric) U-shaped structure. Let us call the theory where the potential in the acceleration region is U-shaped but where the closing of the contours is left open the *weak U-shaped model* and the theory where the U-shaped contours close only in the opposite hemisphere the *strong U-shaped model*. The *strong* U-shaped model implies the *weak* one, but not vice versa. As mentioned above, satellite observations below about 15000 km support the *weak* U-shaped model. The O-shaped model is compatible with the *weak* U-shaped model. On the contrary, to our knowledge there are no observational data directly supporting the *strong* U-shaped model, and the *strong* U-shaped model is in disagreement with the Polar results and the O-shaped model.

3 The "cooperative" model

In an O-shaped potential barrier, electrons are not accelerated but the low energy part of the magnetospheric electron population is filtered out (reflected back) before hitting the ionosphere (Janhunen *et al.*, 1999a). It turns out that in case of a Maxwellian source plasma, the filtering due to a potential barrier produces the same functional form for the low altitude spectrum as an acceleration by a potential drop. Thus, there is no problem in explaining the low-altitude inverted-

V electron spectra by the O-shaped model, provided that the electron energy flux is large enough. However, our current understanding is that in most cases, the magnetospheric thermal electron flux is insufficient to explain the observed intensity at low altitude. This conclusion is mainly based on our conjugate studies between Polar and FAST which are being published elsewhere.

To resolve the intensity problem we propose that above the acceleration region, there are plasma waves causing parallel energization of medium-energy electrons (roughly 50-400 eV). If the parallel energy of an electron is increased by a wave-particle interaction, its pitch angle is decreased and its mirror point moves closer to the ionosphere. The net effect is a buildup of a negative charge cloud of magnetospheric electrons at low altitudes (Alfvén and Fälthammar, 1963). Close to the ionosphere, the cloud is easily neutralized by a displacement of cold ionospheric electrons away from the cloud or by an adjustment in the cold ion density. At some altitude, however, the density of the ionospheric plasma is not sufficient for a complete neutralization, thus the cloud will have, after a partial neutralization, a maximum charge density at a certain altitude. Because of Poisson's equation, the potential corresponding to such a negative charge cloud looks O-shaped.

The center of the O-shaped potential is likely to form at an altitude which is slightly below the region where most of the electron energisation by waves is taking place. Thus, the DC electric field points downward in the region where the waves are giving parallel boosts to electrons, and thus the waves must work against the electric field when giving electrons a downward boost. To make further conclusions one has to assume something about the nature of the waves; let us assume that the wave-particle interaction is *resonant*, i.e. that only those electrons whose parallel velocity is close to the phase velocity of the waves are affected, and that this velocity corresponds to the middle-energy range (50-400 eV, roughly) when transformed to electron energy. The net effect of the downward DC field is then to keep the electrons in the resonant velocity range for a longer time than would otherwise occur, thus helping to extract a larger amount of energy from the waves to the electrons than what would happen without the DC field. That a downward electric field could increase the net amount of particle energisation may sound paradoxical, but this is what the test particle simulation shows. What happens is that the energy extracted from the waves goes mostly to increase the electron potential energy (the waves "push the electrons up a potential hill"). When electrons reach the top of the hill, they are accelerated downward (potential energy is turned to kinetic energy) exactly as in any *weak* U-shaped model (for the definition of *weak* and *strong* U-shaped models, see the end of Section 2).

Thus, we propose that an O-shaped potential is formed as a consequence of wave-particle interactions (Figure 2) and that the potential helps increase the effectiveness of the waves and is also responsible for the functional form of the low-altitude inverted-V electron spectrum. According to our test particle simulations (Janhunen and Olsson, 2000), the "cooperative" model (named so because waves and the potential structure cooperate, both being essential) can explain the observed low altitude spectra quantitatively, provided that suitable waves exist in the ~15000-30000 km altitude range. One interesting feature of the model is that there are separete energisation and acceleration regions for the electrons (Figure 2).

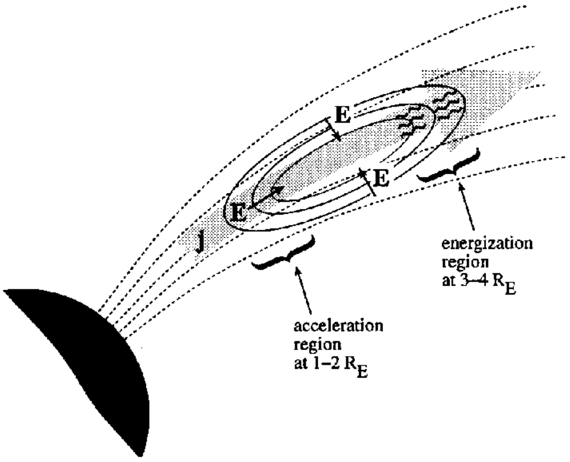

Fig. 2. The "cooperative" model for inverted-V auroral acceleration and self-consistent maintenance of an O-shaped potential structure.

To be relevant, the "cooperative" model requires the presence of plasma waves giving parallel boosts to middle-energy electrons in the ~15000-30000 km altitude range. The presence and precise nature of such waves is still an open question, but we have seen promising events in Polar PWI data: intense broadband electrostatic wave bursts correlated with simultaneous middle-energy electron $T_{\|} > T_{\perp}$ anisotropies. These findings will be published in detail elsewhere.

4 Statistical current-voltage relationship

The relationship between the peak energy and the field-aligned current (FAC) density in inverted-V events is usually called the current-voltage (CV) relationship (Olsson *et al.* , 1996,

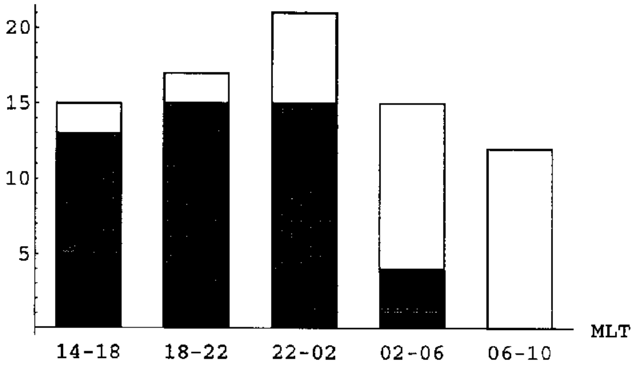

Fig. 3. The number of Freja U-events (black), C-events (gray) and O-events (white) in each MLT sector. In U-events the current and voltage are correlated, in C-events they are not, and in O-events they are anticorrelated.

1998). Here we consider the question from a purely observational viewpoint: how the current j and the voltage (~peak energy) V are correlated. We study 81 inverted-V events using the Freja satellite F7 instrument (Boehm *et al.* , 1994) for estimating both current and voltage, using 31 ms time resolution. The events are distributed in all MLT sectors, except in the noon sector where no inverted-V events are found (Lin and Hoffman, 1979). The results are reported in detail elsewhere (Olsson and Janhunen, 2000a,b), but a main finding is that when all events are considered together, the current j does not, on the average, depend on the voltage V (Olsson and Janhunen, 2000a). Even more interesting is that there is clear MLT dependence (Olsson and Janhunen, 2000b). Let us label events where the current and voltage are positively correlated by "U", events where they are not correlated by "C", and events where they are anticorrelated by "O". In Figure 3 we show the number of each class of events for each MLT sector. We see that in the evening sector, U-type events are rather common, but even there the majority of events belongs to the C-class. Morning sector inverted-V events seem to consist almost exclusively of O-class events. This is an interesting result in its own right. Previous studies made with much smaller datasets have generally suggested linearly correlated current and voltage (Lyons *et al.* , 1979).

It is still an open question what is the relationship between the auroral potential structure and the statistical CV-relationship results. One possibility is that anticorrelative and constant CV-relationships (O and C events) correspond to stable arcs and predominantly O-shaped potential structures, while the rarer evening sector correlative CV-relationship events (U-events) correspond to either *strong* U-shaped potential models (for definition of the term see Section 2) or dynamical cases where inductive electric fields are so important that speaking of a *potential* structure no longer makes sense. It fits in this picture that auroral surge features related to substorms and other auroral activations typically contain higher peak energies than stable arcs; they are also more dynamical and occur mostly in the premidnight sector.

5 Summary

Our recent observations indicate that potential contours that look U-shaped in the acceleration region do not continue up to the equatorial plane, but close at a much lower altitude, below 25000 km or so. (The altitude figures given in this paper should be taken as a rough estimate only.) This implies that there is a downward DC electric field above the acceleration region. To explain this finding without contradicting the existing low-altitude observational data we suggest the "cooperative" model for auroral acceleration. In this model, electrons are energised by random parallel boosts of resonantly interacting plasma waves above 15000 km. An O-shaped potential is responsible for temporarily storing the transferred energy in potential energy form and transforming it into electron kinetic energy in the acceleration region, where the process is exactly as in the classical *weak* U-shaped model. This model can explain both low and high altitude observations quantitatively, provided that suitable waves exist in the ~15000 30000 km altitude range. Our results of the CV-relationship indicate that the morningside inverted-V events are different from the eveningside ones, because in the morningside, the current and the voltage are anticorrelated. This result may well have something to do with the potential structure question. In the future, observational studies should look for evidence on suitable plasma waves in the ~15000-30000 km range. Likewise, the free energy source for the waves, and consequently for the whole auroral acceleration process, should be identified in the magnetosphere.

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