ALTITUDE EXTENSION OF AURORAL POTENTIAL STRUCTURES BY EVENT-BASED AND STATISTICAL STUDIES

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ABSTRACT

Lots of observations below about 13000 km altitude favour the U-shaped potential model above auroral arcs. Recent observational findings above 20000 km indicate, however, that the U-shaped potential related to stable auroral arcs does not usually extend to that altitude. To resolve the dilemma, we have suggested an O-shaped potential model. Here we show how an O-shaped potential can form self-consistently by assuming plasma waves that energise ∼50–400 eV electrons in the parallel direction. The obtained "cooperative" model invokes both waves and O-shaped potential structures in a nontrivial manner to produce inverted-V spectra and auroral arcs, and it is compatible with satellite observations at both low and high altitude.

INTRODUCTION

Auroral arcs are long and narrow structures associated with inverted-V type electron precipitation (e.g., Davis, 1978, Bryant, 1999). From many observations, the accompanying electric field is supposed to form a U-shaped potential minimum above the visual arc (Carlqvist and Boström, 1970, Evans, 1974). In this model, the "bottom" of the U-potential accelerates electrons downward, giving rise to the electron spectral peak which is the characteristic feature defining inverted-V precipitation.

How this electric field pattern maps higher into the magnetosphere has thus far been an open question because of a comparative lack of suitable observations above about 13000-15000 km altitude. In this paper we review recent observational evidence, as well as theoretical and simulation developments, which indicate that the potential contour lines, when altitudes higher than about 13000 km are included, look O-shaped (Figure 1, right panel). In the new model there are parallel electric fields but no net potential drop between the magnetosphere and the ionosphere, or the net potential drop is anyway clearly smaller in magnitude than the depth of the potential well.

EVIDENCE FOR U-SHAPED POTENTIALS

There is a lot of low-altitude evidence for the U-shaped potential model, gathered by satellites in the ∼ 1000–13000 km altitude range (Figure 1, left panel).

(1) One frequently sees convergent perpendicular E-fields in the acceleration region altitude (Mozer et al., 1977, Marklund, 1993). These are interpreted as the sides (flanks) of the U-potential.

(2) Simultaneously with the convergent E-fields, one sees upward moving ion beams. Often one even finds that they are accelerated by approximately the same voltage than the integrated electric field along the spacecraft trajectory (Marklund, 1993, McFadden et al., 1998).

(3) Often, the optical arcs contain flickering which at a closer look consists of small-scale curls and undulations, rapidly streaming westward on the equatorward side of the arc and eastward on the poleward side (Hallinan and Davis, 1970, Trondsen, 1998). The magnitude of the propagation velocity is such that it is consistent to assume it to reflect an $\mathbf{E} \times \mathbf{B}$ drift velocity in the acceleration region, in the flanks of the U-potential (Haerendel et al., 1996, Janhunen et al., 2000).

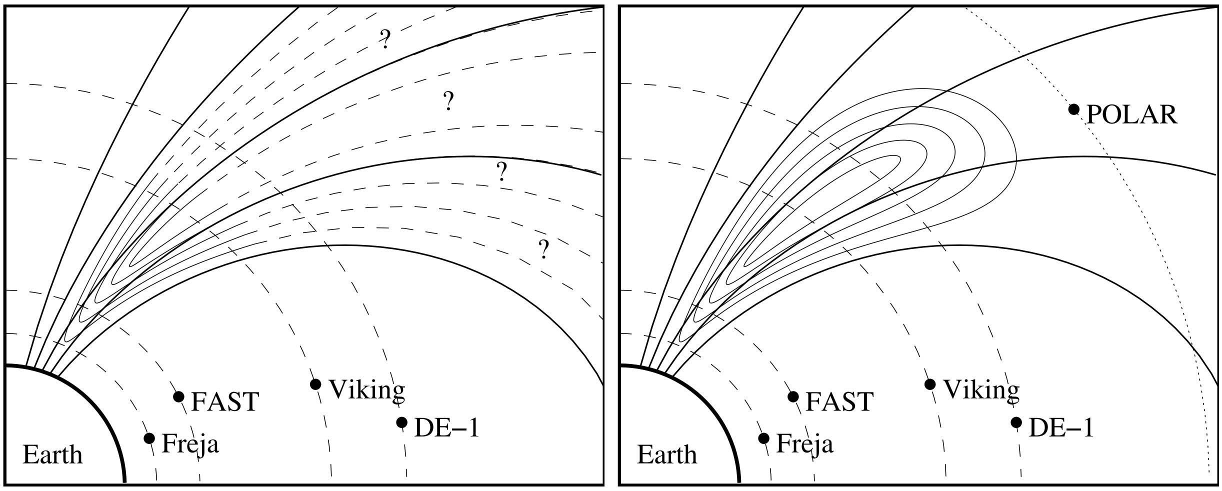

Fig. 1. Before POLAR, data concerning the potential structures above 13000 km were sparse and many workers implicitly assumed an upward continuation of the low-altitude U-model (left). POLAR, however, suggests an O-shaped model (right).

(4) The inverted-V spectral peak by itself can be explained straightforwardly by assuming that the electrons are accelerated through a potential drop (Evans, 1974).

(5) The upward parallel electric field has been directly measured (Marklund, 1993, Mozer and Kletzing, 1998).

Notice that all this evidence is below $\sim$ 13000 km altitude.

EVIDENCE FOR O-SHAPED POTENTIALS

78 POLAR satellite passes at about 20000–35000 km altitude range were studied to find evidence for convergent perpendicular electric fields under non-substorm conditions (Janhunen et al., 1999a). The potential at the satellite was estimated by integrating the measured spin-plane electric field along the spacecraft trajectory. The result was that while a few cases of potential wells of 1-2 kV magnitude were found, not a single case existed among these events that would have indicated a stronger U-shaped potential structure extending above 20000 km altitude. In contrast, potential wells observed at lower altitude by a similar technique can easily have magnitude 5-7 kV and more. To explain the observation, we suggested that the U-shaped potential contours close below about 20000 km, thus forming an O-shaped potential (Figure 1, right panel). We do not know any other *potential* model to explain the lack of convergent E-field above 20000 km than the O-shaped model. The only other possible way to explain the observation would be to assume significant inductive electric fields, but we do not consider this as a plausible explanation, e.g. because sometimes auroral arcs can remain seemingly stationary for half an hour and more.

To approach the problem from slightly different viewpoints, we studied POLAR/FAST magnetic conjunction events (Janhunen et al., 1999b). In these events, the detailed electron distribution functions measured above 20000 km (POLAR/HYDRA) and below 4000 km (FAST) are available. Unfortunately, POLAR DC electric field observations can not be reliably used for these events. In these events, although the U-shaped model can explain the total precipitating energy flux magnitude, it cannot explain the shape of the inverted-V spectrum versus the high altitude distribution function. Furthermore, there is evidence for ion beams of only 1-2 keV energy in these events, although the accelerating voltages as determined from the inverted-V peak positions are clearly higher. These findings are consistent with the O-shaped model (allowing for a possible residual U-potential of 1-2 kV magnitude).

Another, much more indirect possible evidence for the existence of O-shaped potentials are provided by the morningside anticorrelative current-voltage relationships that were recently found in statistical studies using FREJA electron data (Olsson and Janhunen, 2000ab). This is an interesting finding, although its

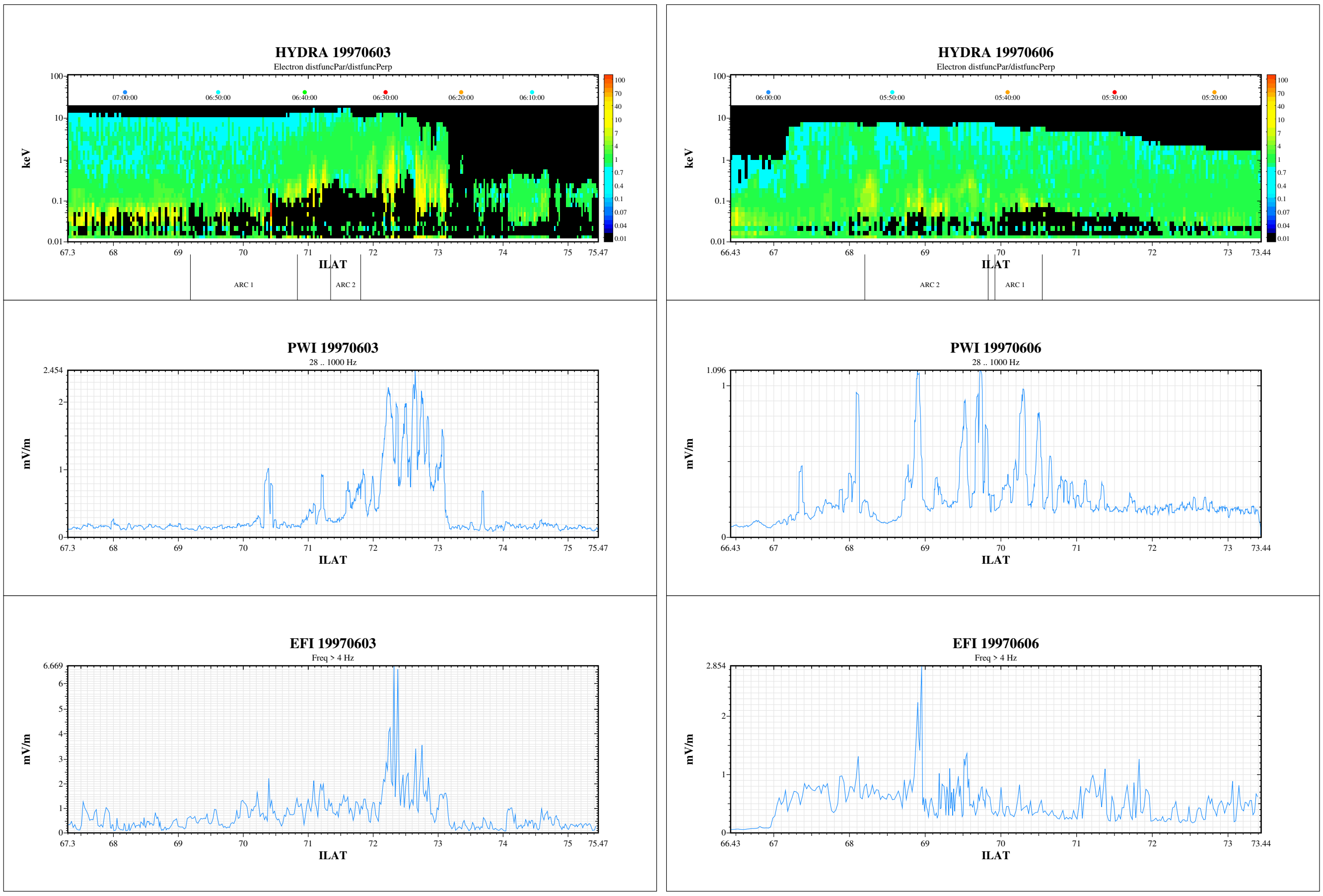

Fig. 2. POLAR satellite data for June 3, 1997, 06:05–07:05 UT (left panel) and June 6, 1997, 05:20–06:00 (right panel). Top row: HYDRA electron anisotropy $f_{||}/f_{\perp}$ where f is the electron distribution function. Cases of $f_{||} \gg f_{\perp}$ are seen as lighter shade. Middle row: Plasma Wave Instrument (PWI) electrostatic power in the 28–1000 Hz frequency range. Bottom row: Electric Field Instrument (EFI) power, 4-10 Hz frequency range. Notice the clear temporal correlation between occurrences of high electron anisotropy ($f_{||} \gg f_{\perp}$) and enhanced wave power.

exact role in the potential structure question is still a bit unclear.

We emphasise that the evidence favouring the O-shaped model concerns *stable* auroral arcs only. The reason for excluding dynamically varying arcs (usually related to substorms) in this stage of the study is that it is more difficult to obtain observational evidence because the motion speed of dynamical arcs can exceed the velocity of a high-orbiting spacecraft, thus introducing a spatio-temporal ambiguity problem. The forthcoming CLUSTER-II mission might help us around this difficulty. Theoretically, however, there is no apparent reason why the O-shaped model could not be applicable in dynamical cases as well.

WAVE BURST OBSERVATIONS

When studying the POLAR/FAST conjunctions (Janhunen et al., 1999b), we found a clear temporal correlation between broadband (4-1000 Hz) electrostatic wave bursts and middle-energy ($\sim$ 50-400 eV) electron distribution anisotropies (Fig. 2). This may provide a clue about how the electron acceleration machinery works. The correlation is clear, and to explain it, we suggest that the observed broadband electrostatic wave bursts cause the observeded $T_{||} > T_{\perp}$ electron anisotropy by accelerating middle-energy electrons in the parallel direction. Below we will explain what role the wave bursts might have in the maintenance of the O-shaped potential. Unfortunately, the instrumentation does not yet allow us to deduce the more detailed characteristics of the waves such as their phase velocity, wavelength, or the character of

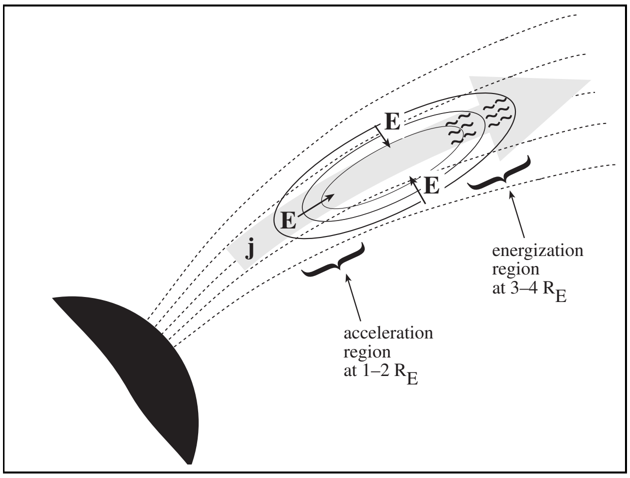

Fig. 3. Schematic picture of the "cooperative" model. Notice the difference between acceleration and energisation region.

the bursty behaviour (spatial or temporal).

TEST-PARTICLE SIMULATION AND "COOPERATIVE" MODEL

To see explicitly how electrons behave in U- and O-shaped potentials, a test particle simulation was carried out (Janhunen and Olsson, 2000). The simulation was validated by comparisons with exact analytical theory in cases where the electron motion is adiabatic. For going beyond analytical theory results, the simulation model allows us to add any amount of random parallel boosts to accelerate electrons in some altitude and energy range in the parallel direction. When measured POLAR/HYDRA data is used as simulation input, the outcome is that both U-shaped and O-shaped potentials produce almost the same electron precipitation when random parallel boosts are included, and the generated electron spectrum is in quantitative agreement with FAST measurements magnetically conjugate to the input POLAR data. The U-potential alone would produce about the correct energy flux, but not a realistic shape for the spectral peak. The random boosts alone (i.e., without any potential at all) would produce a spectral shape that looks unrealistic in a different way (too broad peak).

The physical explanation for this result, which at first may look surprising, is that in the case of an O-potential, the waves (modelled by the random parallel boosts) must do work against the downward electric field in the upper part of the "O". In other words, they push electrons up a potential hill. Therefore, electrons can stay in the resonant velocity range for a longer time than without the potential hill (since the electron has a negative charge, a negative O-shaped potential well is a "hill" if one thinks of electron energy). Thus, the potential helps extract more energy (kinetic + potential) from the waves. This energy is released, i.e. transformed into kinetic energy, in the lower part of the "O", where the electric field points upward. We call the upper part of the "O" the *energisation region* because that is the altitude range where waves transfer energy to the electrons. The energy is first stored as electron potential energy. Following the usual terminology, we call the lower part of the "O" the *acceleration region*. It is only there that the electrons are finally accelerated to their final precipitation speed. We call this the "cooperative" model (Figures 3 and 4) because plasma waves and potential structure cooperate in a nontrivial manner to produce the inverted-V spectra and auroral arcs.

PRIMARY CHARGE CLOUD

Thus far we have shown that realistic electron spectra can be produced by O-shaped potentials if suitable waves are also present to cause pitch angle scattering. We shall now consider the reverse question: what can create and maintain an O-shaped potential.

To explain the formation of an O-shaped potential, a negative charge cloud is needed. Let us start by assuming the existence of the plasma waves that decrease the pitch angle (e.g., by increasing the parallel

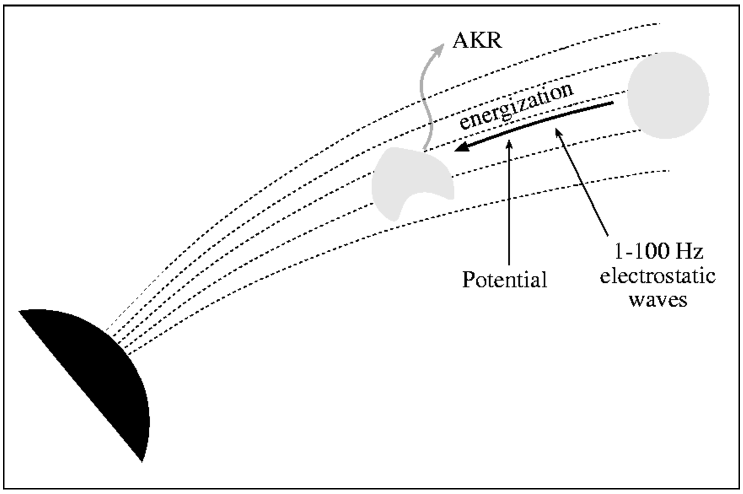

Fig. 4. In the "cooperative" model, plasma waves cause parallel acceleration of middle-energy electrons, modifying the electron distribution function, causing an O-shaped potential, inverted-V spectra and secondary phenomena such as AKR emission

energy) of the middle-energy electrons. These are the same waves that were assumed to exist in the previous section. For the middle-energy electrons, the parallel temperature becomes larger than the perpendicular temperature, and the mirror points move towards the ionosphere. Thus, a negative charge cloud forms, whose density is the largest at the ionosphere (Alfvén and Fälthammar, 1963). Notice that a primary charge imbalance formed by particle population A can be neutralised by another population B, if B is colder than A and if the original density of B exceeds the charge density imbalance. This is because under the listed conditions, a field-aligned potential pattern needed to displace the B-particles to maintain quasineutrality has a smaller magnitude than the average kinetic energy of the A-particles.

In our case, cold ionospheric electrons neutralise the ionospheric end of the primary charge cloud, up to an altitude where the cold ionospheric plasma density drops to a value which is equal to the primary charge cloud density. This altitude then becomes the locus of the acceleration region. The result is a negative charge cloud whose center is just above the acceleration region. The corresponding potential is O-shaped and centered at the same altitude. Thus, we have shown a self-consistent mechanism for the formation of the O-shaped potential, and how it can produce electron inverted-V spectra. The only initial assumption was the existence of plasma waves which energise middle-energy electrons in the parallel direction above about 13000-15000 km altitude.

SUMMARY

We have shown that the "cooperative" model explains all or most of earlier findings that have been used to support the U-shaped potential model. This is not surprising, since the lower part of the O-potential *is* U-shaped. However, the new model also explains new observations made above 20000 km altitude (the lack of convergent E-field, etc.). For the model to work, we need plasma waves that cause pitch angle scattering of middle-energy ($\sim$50-400 eV) electrons above about 13000-15000 km altitude. We have observations indicating that the waves exist, but their exact character remains to be determined and their compatibility with the proposed mechanism to be verified.

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