Lesson 5: M-I coupling and auroral arcs

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Optical methods in auroral physics research
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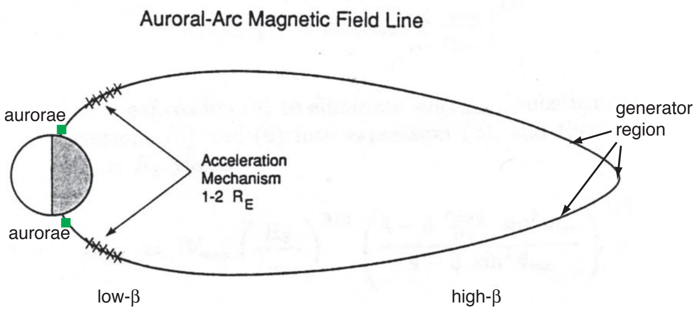
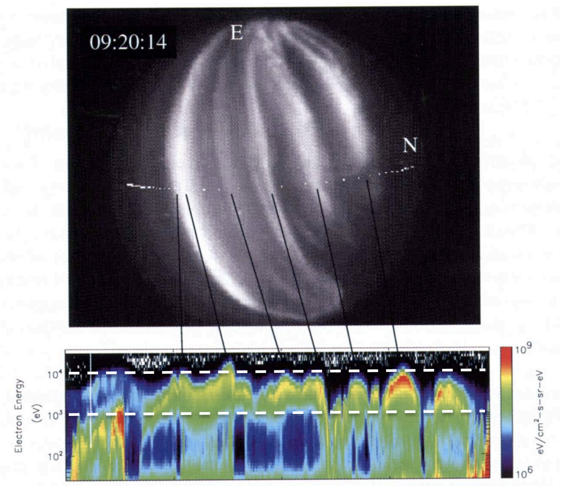
Energy of particles in discrete aurora

Energy of plasma sheet and PSBL electrons is typically smaller than for electrons producing aurora in the ionosphere. Further energy may come from:

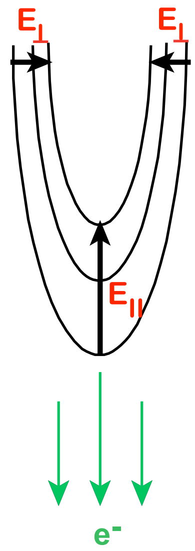
- Auroral acceleration region at altitudes of ~1 – 3 R_E
- During substorms, from magnetic reconnection in the tail at NENL (X~20-30 R_E)
- From waves, especially from kinetic/inertial Alfvén waves



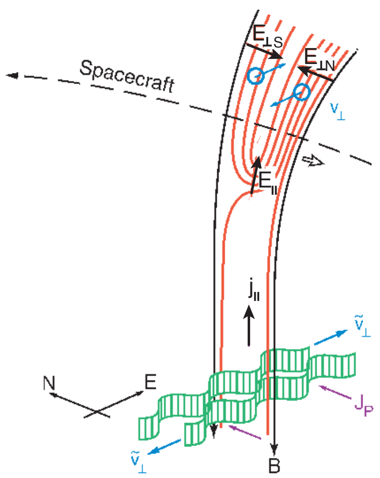
Acceleration of auroral particles by a quasi-static electric field structure (potential drop)



Electron energy between 1 and 10 keV shown by dashed lines.



U-shaped potential structure



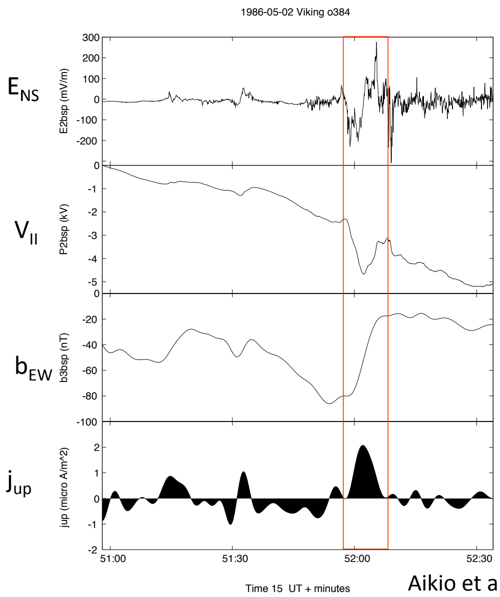
By integrating the electric field along the path, one gets the potential variation. Since V =∫ **E**·**dl** we get

$$\int E_{\perp N}\, dl_{\perp N} = \int E_{\parallel}\, dl_{\parallel} = -V_{\parallel}$$

and satellite measurement of electric field can yield the parallel potential drop $V_{\parallel}$ below the satellite.

Electric fields (arrows), constant potential contours (red) and the upward field-aligned current in the *auroral accelration region* (Auroral Plasma Physics, 2002).

Acceleration of auroral particles by a quasi-static electric field structure (potential drop)



Satellite measurements at altitudes of 1-3 R_E (the acceleration region) have confirmed the picture by electric field, particle and magnetic field measurements, e.g. Mozer et al. (1980), Temerin et al. (1981), Weimer (1985), Marklund et al. (1997), Carlson et al. (1998), Marklund et al. (2001), …

Auroral arcs are associated with **upward FAC** from the arc!

Aikio et al. (1996)

Upward FAC and $V_{||}$

To find the relationship between $j_{||}$ and $V_{||}$ we need the kinetic theory (not MHD). Kinetic theory utilizes the particle distribution function f(**r**, **v**, t), which is a concept of statistical physics. Knight (1973) and Lemaire and Scherer (1974) derived the current carried by magnetospheric electrons, undergoing adiabatic motions:

$$j_{\|} = j_{th}\frac{B_i}{B_m}\left[1-\left(1-\frac{B_m}{B_i}\right)\exp\left(-\frac{eV_{\|}}{E_{th}\left(\frac{B_i}{B_m}-1\right)}\right)\right]$$

where B_i is the magnetic field at the ionospheric altitude and B_m is the magnetic field in the magnetosphere. The thermal current j_{th} is the current that is carried by preciptating electrons without any potential drop (it is carried by electrons, whose pitch angle in the equatorial plane is small enough so that their mirror point is down in the ionosphere and hence they are lost in the ionosphere):

$$j_{th} = en\left(\frac{E_{th}}{2\pi m_e}\right)^{\frac{1}{2}}$$

Knight equation

When $k_B T \ll eV_{\|} \ll \frac{B_i}{B_m} k_B T$, the Knight equation can be approximated by

$$j_{\|} = \frac{ne^2}{(2\pi m_e E_{th})^{\frac{1}{2}}} V_{\|} = K V_{\|}$$

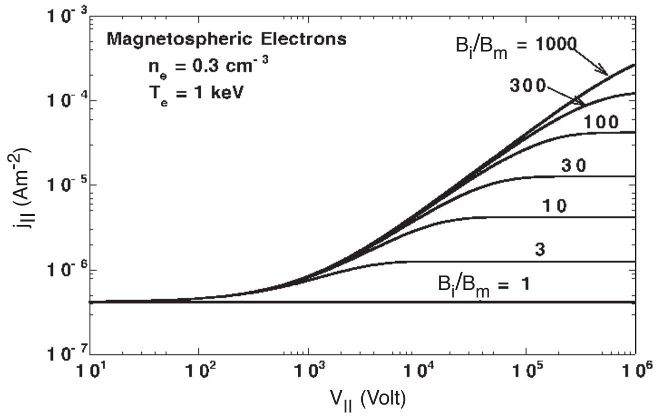
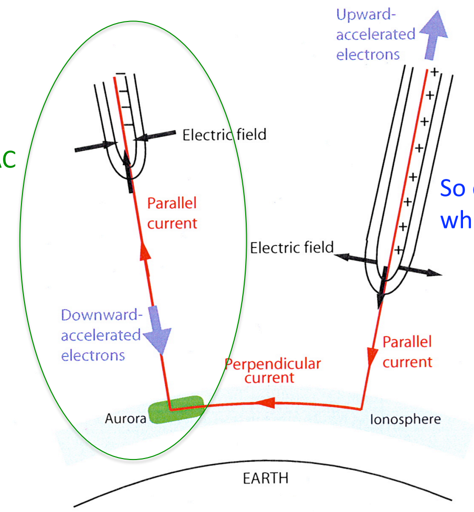


Figure: The field-aligned current density away from the ionosphere (upward) as a function of the parallel potential drop for various values of the mirror ratio B_i/B_m. Which part corresponds to the equation above?

Current system associated with auroral arcs

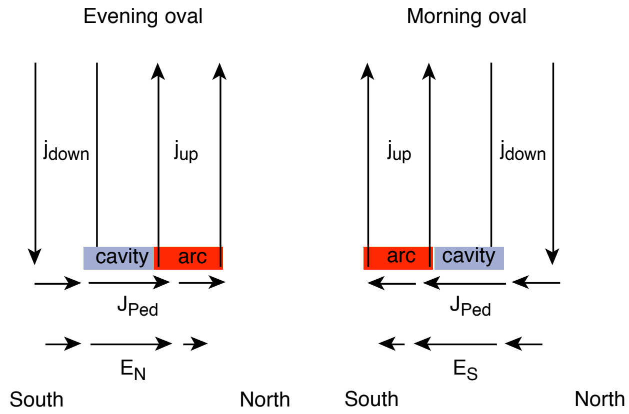
Auroral arc and upward FAC



So called return current, which is directed downward

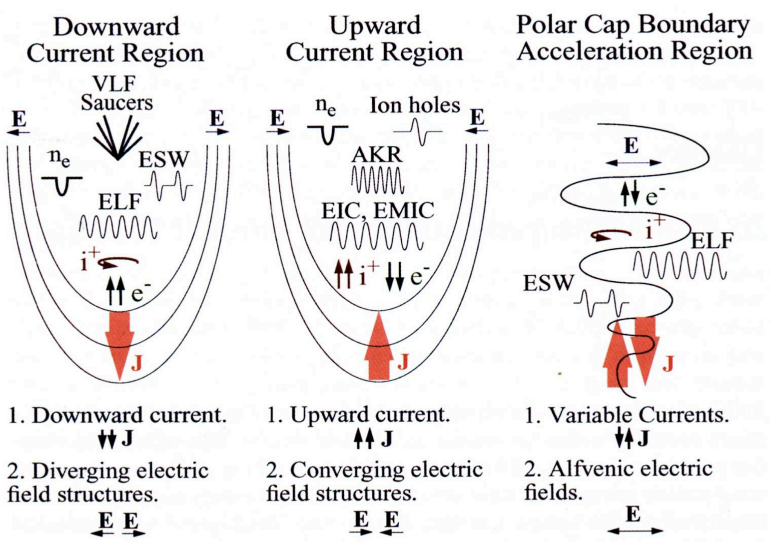
Figure 7.3: Schematic figure of the auroral current circuit with negative and positive potential structures corresponding to convergent and divergent high-altitude electric fields, respectively (Marklund, 2001).

Arc current systems in the dusk and dawn oval



- Density cavity and the enhanced ionospheric electric field are not always observed
- An auroral arc and the upward FAC may be formed also at a convection reversal boundary.
- Opgenoorth et al. (1990), Aikio et al. (1993), Aikio et al. (2002)

Schematics from high-altitude satellite measurements



Carlson et al. (1998)

Acceleration of auroral particles by inertial Alfvén waves

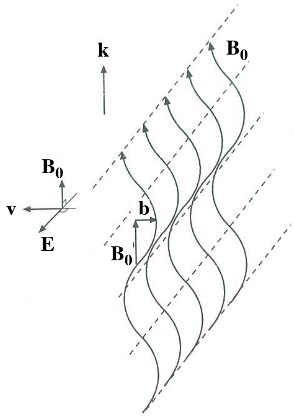
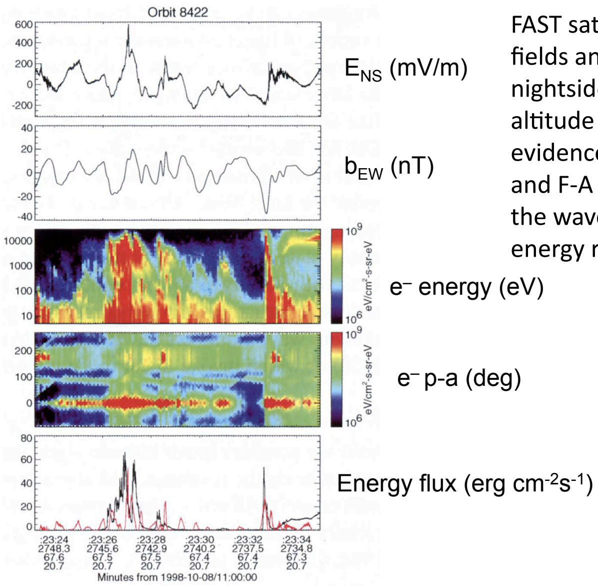


Figure: Shear Alfven waves are transverse MHD plasma waves that travel along **B**.

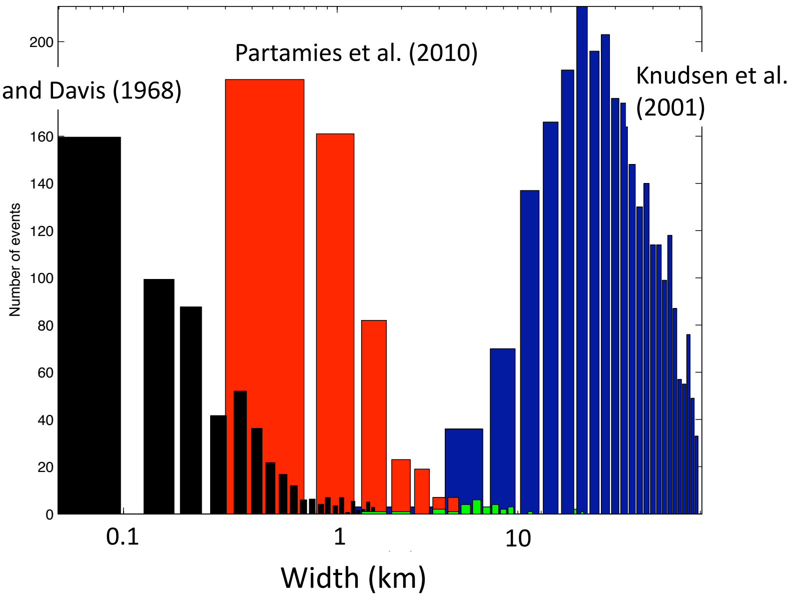
When the perpendicular scale length of the Alfven waves becomes too small, the ideal MHD breaks down and the waves become dispersive, which means that different frequencies travel at different velocities. This leads to a change in the nature of Alfven waves, in particular a parallel wave electric field is introduced. This $E_{||}$ may accelerate particles.

Acceleration of auroral particles by inertial Alfvén waves



FAST satellite measurement of wave fields and electrons close to the nightside polar cap boundary at an altitude of about 2740 km showing evidence of inertial Alfvén waves and F-A electrons accelerated by the waves. Note that electron energy range is broad.

Widths of auroral arcs



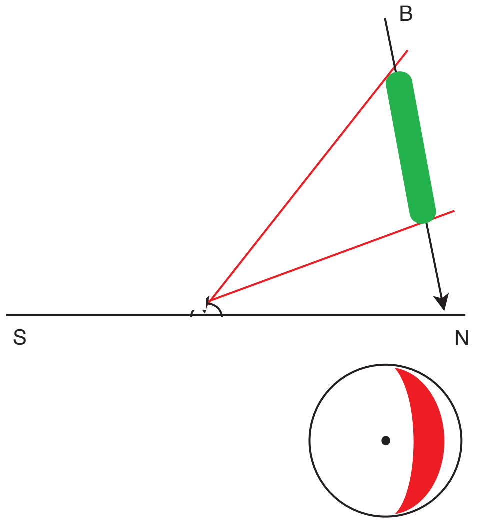
Width of arc and all-sky image

Group task 5: How does the 2D all-sky image map to the sky? Make a sketch in the magnetic meridian plane! Which of the two boundaries is the more important one for the location of the arc?

Result

When the arc is located to the north or to the south of the magnetic zenith, the width in the ASC image is an apparent width and only the outer boundary from the zenith gives an estimate of the location of the arc.

All-sky camera measuring an auroral arc

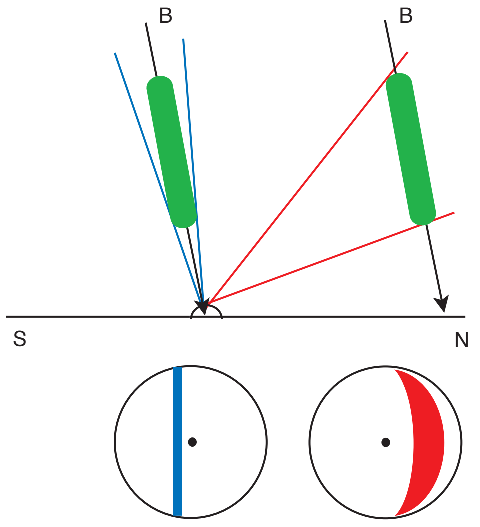


How to measure true width?

When the arc is located to the north or to the south of the magnetic zenith, the width in the ASC image is an apparent width and only the outer boundary from the zenith gives an estimate of the location of the arc.

When the auroral arc (narrow in the north-south direction and with some vertical extent) is **in the magnetic zenith** and the camera is directed towards the magnetic zenith, the true width of the arc can be estimated.

All-sky camera measuring an auroral arc



Some theoretical considerations related to observed widths of auroral arcs

Electrostatic coupling between the magnetosphere and the ionosphere:

- Natural scale length L of electrostatic mapping between the ionosphere and magnetosphere (Weimer, 1985) depends on Pedersen conductance Σ_P and field-line conductance K

$$L = \sqrt{\frac{\Sigma_P}{K}}$$

and K is

$$j_\parallel = \frac{ne^2}{(2\pi m_e E_{th})^{\frac{1}{2}}} V_\parallel = K V_\parallel \ ,$$

It has been estimated that L varies between **100 km** (e.g. Lysak, 1991) and 340 km (Borovsky, 1993) => large-scale inverted-V's could be explained.

Some theoretical considerations related to observed widths of auroral arcs

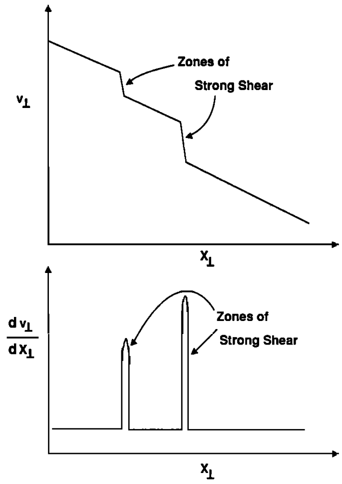
The parallel electric field in **inertial Alfvén wave** is given by:

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

where λ_e is the electron skin depth and $k_{||}$ and $k_\perp$ are parallel and perpendicular wavenumbers. Typically $\lambda_e k_\perp$ ~1. $E_{||}$ can be 1 mV/m over wavelengths of more than 1000 km. The potential drop in the wavefront of the inertial Alfvén wave can be of the order of kilovolts, though more typically hundreds of eV. Typical widths are **~1 km**.

Some theoretical considerations related to observed widths of auroral arcs

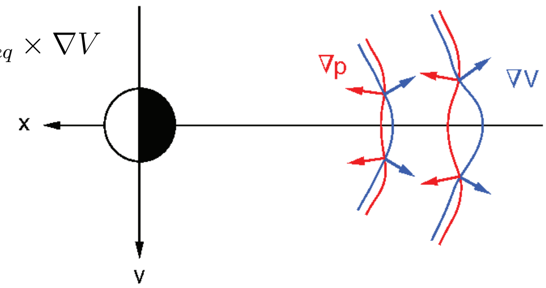
Velocity shears (plasma vorticity given by ∇x **v**) can act as a MHD generator and drive F-A currents. Borovsky (1993) estimated that typical shear widths in in the low-latitude boundary layer (LLBL) give widths of ~**130 km** and in the plasma sheet **3 – 50 km**.



Some theoretical considerations related to observed widths of auroral arcs

Pressure gradients in the plasma sheet may be associated with FAC:

$$\int_{eq}^{ion} \frac{j_\parallel}{B} = -\frac{\mathbf{B}_{eq}}{B_{eq}^2} \cdot \nabla p_{eq} \times \nabla V$$



Borovsky (1993) estimated that for 4 keV ions in the plasma sheet (X= -12 Re) the minimum pressure gradient width (corresponding to ion gyroradius) would map to a value of ~**3 km** in the ionosphere.

Some theoretical considerations related to observed widths of auroral arcs

Conclusion: Several mechanisms produce auroral arcs with widths above 1 km, but small-scale (< 1 km) widths are difficult to explain!

Summary

Ground-based optical observations show that multiple scale structures are often observed in aurora.

To explain those, probably several different generation and acceleration mechanisms are needed.

At the moment, we don't know the process to produce auroral arcs => **Key challenge for magnetosphere-ionosphere coupling studies.**