Auroral Physics

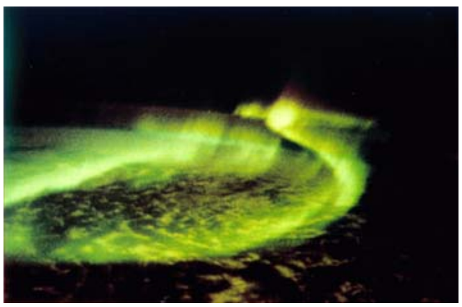
Basics:

- The aurora are caused by electrons hitting the upper atmosphere / lower ionosphere at 100-250 km in altitude.
- Clearly visible to the naked eye.
- Occur at 65-75° geomagnetic latitude both north (aurora borealis) and south (aurora australis) ⇒ Makes <u>auroral oval</u>
- Aurora move further south during geomagnetically active times → solar input very important.
- Wide ranging morphology of forms: stable arcs, flickering (~100 Hz), pulsating (1-10 s) and "substorm breakup" arcs
- Source population of electrons is the Earth's plasma sheet   Kletzing [2003]
  ↳ occur on <u>closed</u> field lines, but the last ones just before <u>open</u> polar cap field lines.
- Strongest on nightside: 2000 - 0200 MLT

Auroral Forms

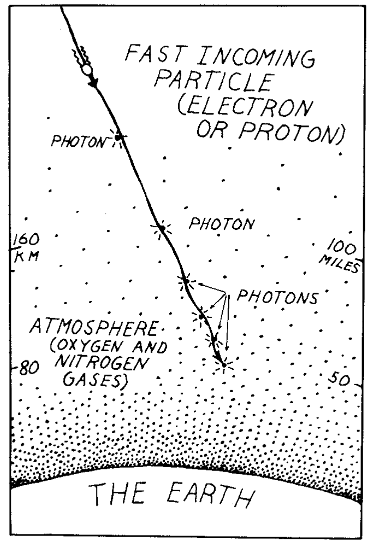
Aurora From Space

Auroral electrons line up along the Earth's magnetic field lines due to v x B force
Note that red aurora is usually at higher altitude and blurry due to long lifetime.

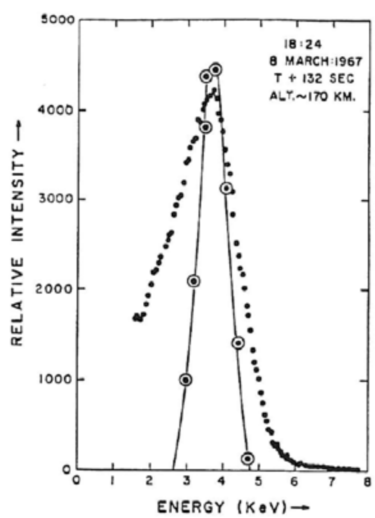


Auroral Light Emission

- Electron collisions with atmospheric neutrals produces auroral light.
- Most common emissions are the 6300 Å (red) and 5577 Å (green) lines of atomic oxygen.
- Electrons have energies of 0.1-10 keV.



Evans [1968] made measurements that were well resolved in energy. The data were consistent with a delta funcition in energy convolved with the instrument response.



History of Measurements

- Ancients had many explanations for visual observations

Magnetometer measurements in regions near the aurora showed clear deflections when aurora were present.

Kristian Birkeland (1867-1917) used a terrella - a miniature Earth with a magnetic field in a vacuum - and found That by shining electron beams on it, he could make it glow in a manner similar to that of the aurora.

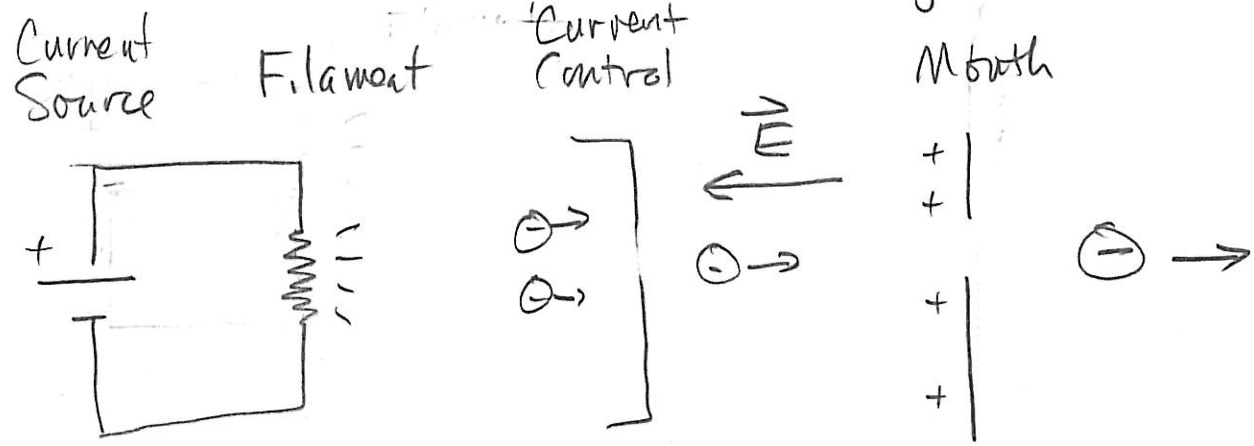
In the late 1950's, with access to space, came the first direct measurements.

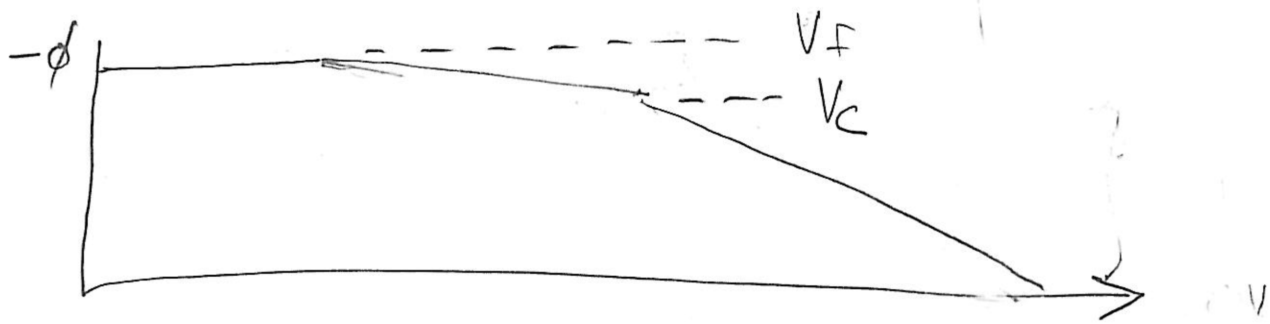
McIlwain [1960], Van Allen's student published the first measurements of the electrons that cause the aurora.

→ non-Maxwellian in nature
→ energies of 1-10 keV, but not good enough energy resolution to say much more.
→ Suggests that an electrostatic potential drop could explain observations - only mentioned in the abstract and little elsewhere in the paper.

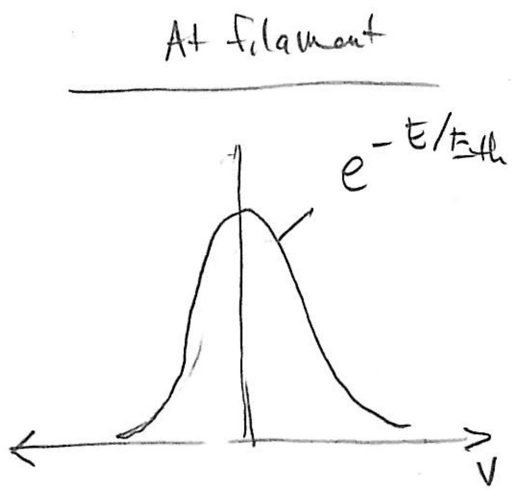
As the 1960's progressed, more and better measurements
→ clearly non-Maxwellian
→ mono-energetic peak. → Evans [1968]

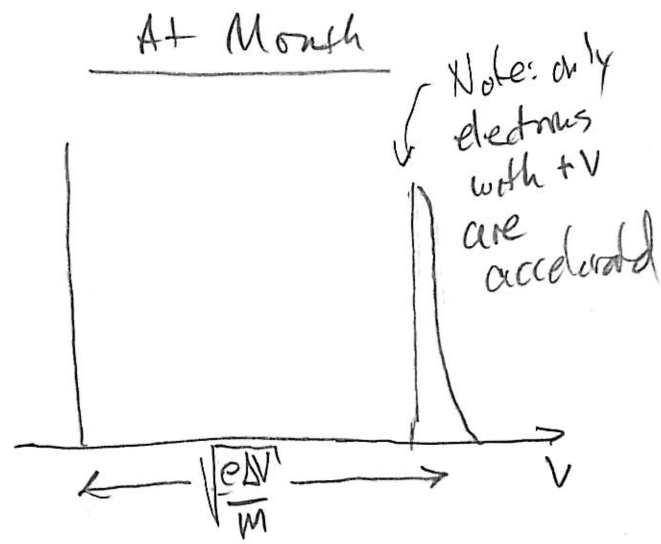
Evans also suggested a potential drop. Why was this. Consider an electron gun.





This arrangement takes a Maxwellian at the filament and turns it into a beam:





This looks a <u>lot</u> like what Evans [1968] reported. But, there was fierce resistance to this idea!

Why? It's a <u>collisionless</u> plasma, so $E_{\parallel}$ cannot exist!

$$J_{\parallel} = \sigma_{\parallel} E_{\parallel} \Rightarrow E_{\parallel} = J/\sigma$$

Since it's collisionless $\sigma \rightarrow \infty$ and $J_{\parallel} \rightarrow 0$

This was a widely held opinion <u>all</u> through the 1960's!

Measurements continued. In the 1970's satellite measurements became more common (needed a polar orbit to see auroral precipitation:

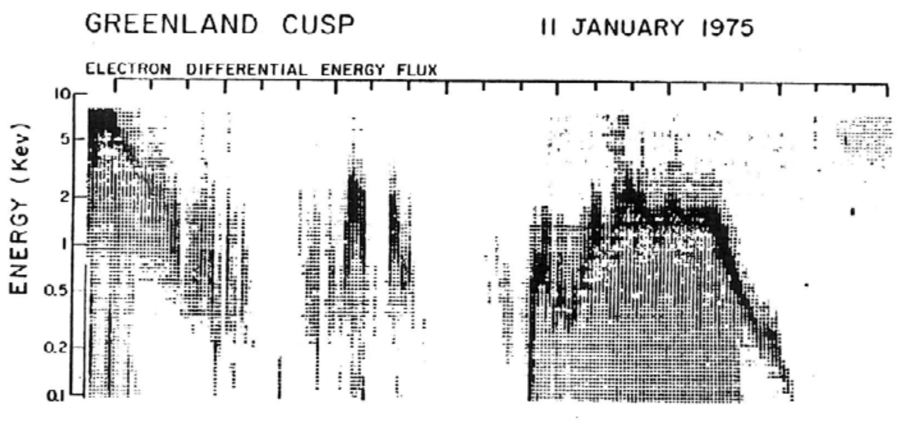
⇒ Inverted "V" term coined

This led to another objection – how could there be particles below the energy peak that were precipitating?

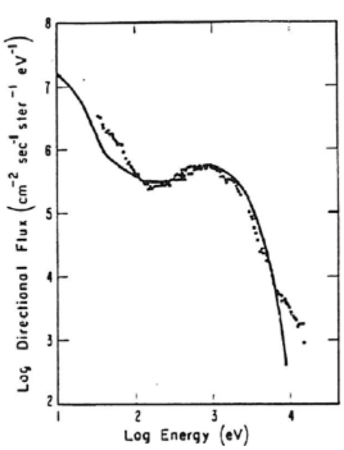
⇒ Evan [1974] calculated a spectrum that showed it was.

⇒ Knight [1973] found a relationship based on current closure – current flows upward (electrons downward) and the only place it can close across field lines is at the lower ionosphere where collisions are important. <u>But</u> mirror force keeps most electrons from getting there ⇒ acceleration

Satellite measurements identified the "inverted –V' signature coined by Frank and Ackerson [1972]. It is shown here in rocket data from 1975.



Evans [1974] showed that degraded primaries and backscattered electrons from collisions in the much denser (and collisional) lower ionosphere could fill in below the 'monoenergetic peak'. They were trapped between magnetic mirror below and electrostatic potential above.



must occur to get electrons to ionosphere. (5)
This is, however, only an existence proof – doesn't explain the plasma physics.

⇒ Iijima & Potemra identify the region 1 and region 2 currents. Supports Knight [1973] ideas.

S3-3: First satellite with good $\vec{E}$ measurements. Sees large $\vec{E}_\perp$ associated with electrons, waves, and upgoing ions. Fields are called "electrostatic shocks" but they aren't shocks.

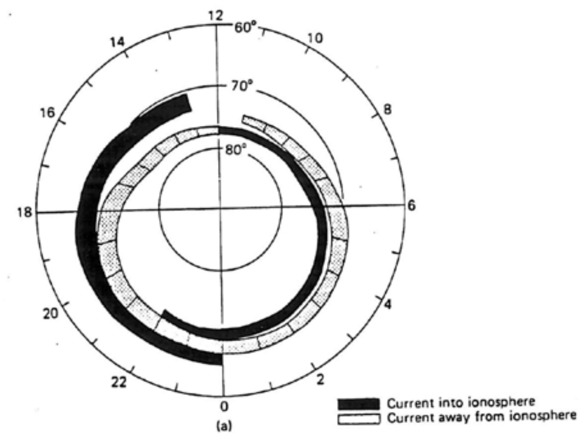
Early 80's

S3-3 data brings about the canonical picture of quasi-static auroral electric field configuration. Establishes region as 2000 km to above 800 km.
Measurements continue:

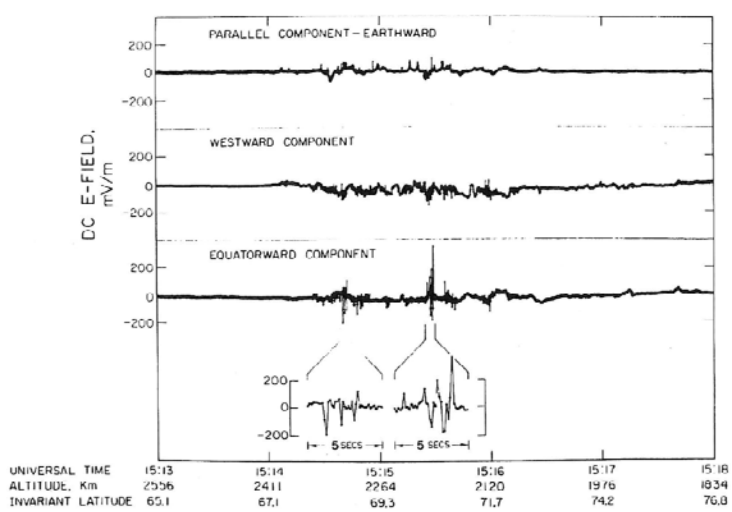
Viking 1986 – high altitude
DE-1 and DE-2 – 1981

These provide much better particle measurements with higher time resolution and more altitude coverage in the acceleration region

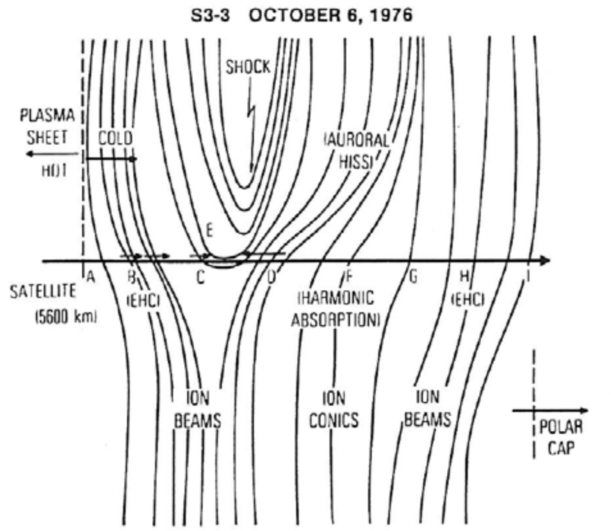
Iijima and Potemra [1978] analyzed satellite magnetometer data in terms of field-aligned currents and saw clear correlation with the auroral oval and named these the Region 1 and Region 2 current systems.



S3-3, launched in 1977, had one of the first, high-quality electric field experiments on a satellite. It detected "elctrostatic shocks" – large perpendicular electric fields.



The quasi-static potential acceleration picture from S3-3 still holds up today.



Theoretical Models

With the results of S3-3 and other observations, theorists began to work on models of auroral acceleration.

In the late 1970's, voltage driven models began to appear:

Lundin and Sandahl [1978] extended the Knight relation to be in terms of energy flux rather than current

Swift [1976] had a "shock-like" model of auroral acceleration

Lyons [1980, 1981, 1982] had a series of model results giving the scale of auroral arcs.

Several authors work on how to produce anomalous resistivity to support the potential drop.

In the 80's, PIC simulations became popular. These could produce "double-layer" potential drops, but were very short along the field line an fairly unrealistic

During this period, the Alfvén wave emerged as a mechanism that could accelerate electrons:

Hasegawa [1976] first suggests that kinetic effects are important.

Goertz and Boswell [1978] shows that the "inertial" Alfven wave can have a parallel E that could accelerate electrons

$$\omega = \frac{V_A k_z}{\sqrt{1 + k_\perp^2 c^2 / \omega_{pe}^2}}$$

This has a parallel electric field:

$$E_{\parallel} = E_{\perp} \frac{k_{\parallel} k_{\perp} (c/\omega_{pe})^2}{1 + k_\perp^2 (c/\omega_{pe})^2}$$

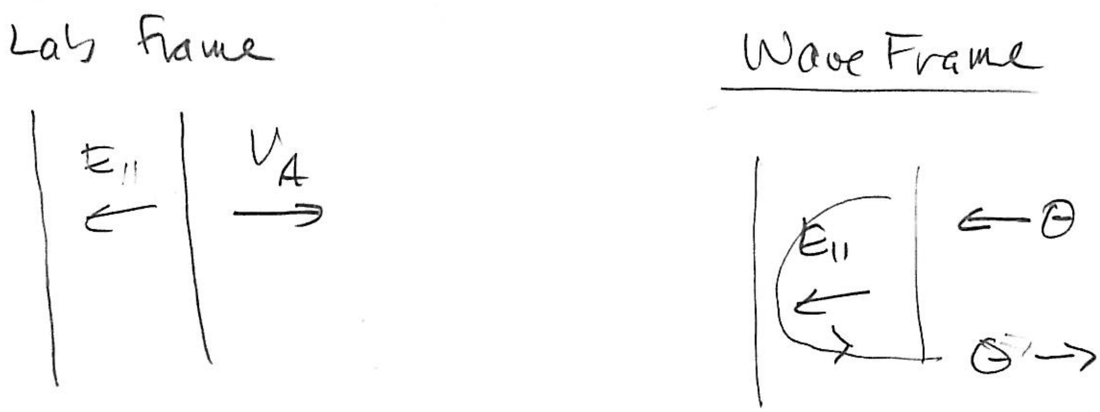
where $\lambda_e = c/\omega_{pe}$ is the skin depth.

Lysak in a series of papers [1983, 1985, 1986] showed with simulations that Alfven waves could set up potential drops <u>if</u> "anomalous resistivity" was included.

<u>The 1990's</u>: Two important satellites were launched: Freja in 1992 and FAST in 1996.

Freja provided many detailed measurements
→ downward current region corresponded to upward electrons and "black" aurora
→ re-ignited interest in Alfvén waves

Kletzing [1994] showed that Alfvén waves could create auroral electrons at lower energy via a "one-bounce" Fermi process



Calculations matched rocket data

FAST provided by far the most complete set of measurements in the acceleration region to date
— confirmed basic S3-3 picture
— showed that upward-going electrons are a <u>very</u> common feature
— confirmed the role of Alfvén waves

<u>TODAY</u>: FAST measurements are the best so far, and still being used. However, we still DO <u>NOT</u> have a self-consistent theory of auroral acceleration!

Outstanding Questions

- How is potential distributed along the field line
- How do quasi-static arcs evolve? Are they started by Alfvén waves or some other mechanism
- What supports the potential drop? No good models
- Is the system current or voltage driven?
- Which processes in the plasmasheet drive the aurora
- Dynamics??