Hawes ①

Lecture #16: Auroral Physics (In Memory of Craig Kletzing)

I. Basic Facts

A. Characteristics of the Aurora

1. The glow of the aurora is caused by energetic electrons (~ 1 keV) streaming downward along the Earth's magnetic field lines
   a. Collisions with atoms in the upper atmosphere & lower ionosphere generate excited states
   b. Excited atoms relax by emitting radiation
   c. Common emission lines: 6300 Å (red), 5577 Å (green)] atomic oxygen

2. Visible to the naked eye
   a. Has fascinated humanity since ancient times

3. Occurs at 65°–75° geomagnetic latitude in both the north (aurora borealis) and the south (aurora australis)
   a. Creates the "auroral oval"

216 Y. I. FELDSTEIN and G. V. STARKOV (1967)

More active → expands equatorward

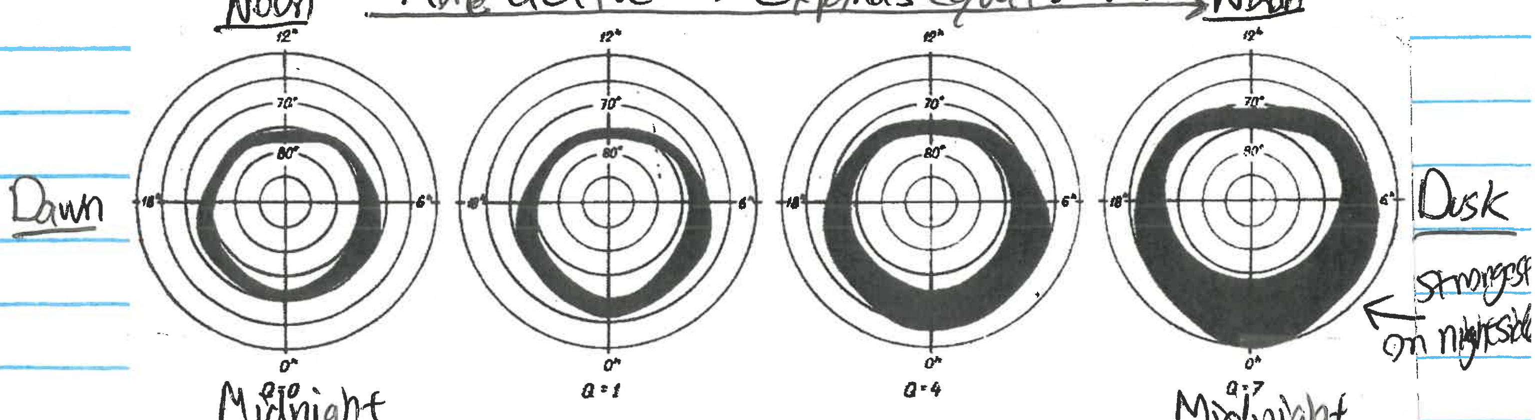


FIG. 5. AN AURORAL BELT AT DIFFERENT DEGREES OF GEOMAGNETIC ACTIVITY.

IA (Continued)

4. The aurora are driven by input from the variable Solar wind and other activity (Coronal Mass Ejections, CMEs)

   a. Constitutes a key process in Magnetosphere-Ionosphere coupling (M-I coupling), which determines how the Earth responds to forcing by solar activity

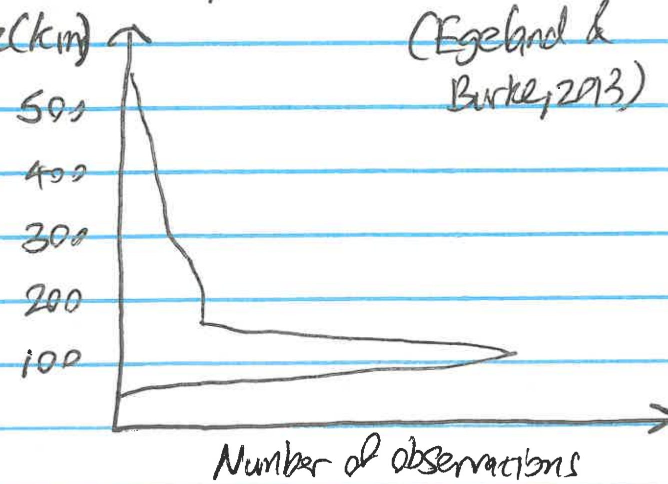
5. Auroral Morphology: Variety of forms
   a. Stable Arcs
   b. Flickering arcs (~100 Hz)
   c. Pulsating arcs (1–10 s)

6. Same population for electrons: Plasma Sheet

   a. Aurora occur on closed field lines, adjacent to the open field lines of the polar cap.

7. Altitude:

   a. Generally observed over 100–250 km in altitude
   b. Diffuse (red) auroras extend up to ~500 km



I. (Continued)

B. Drivers of the Aurora

1. Three magnetospheric drivers for the aurora have been identified.

① Precipitation of very energetic magnetosheath particles in magnetospheric boundary layer:
   i) Day side (Eastman, etal, GRL, 1976)
   ii) Nightside (Kennel & Petschek, JGR, 1966; Kennel, Rev Geophys, Space Phys, 1969)

② Parallel electrostatic potential drops leading to quasi-static, magnetic field-aligned currents (Iijima & Potemra, JGR, 1976)

③ Energetic electrons accelerated by Alfvénic fluctuations, either as
   i) Field-Line Resonances (standing Alfvén waves) (Samson, etal, JGR 1991)
   ii) Earthward propagating Alfvén Waves
   (Hasegawa, JGR, 1976)
   (Goertz & Boswell, JGR, 1979)

~~~ → indicates University of Iowa researcher.
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II. History of Auroral Measurements and Theories

A. Early Observations

1. Ancient peoples in the polar regions observed the aurora routinely
   a. Religion tried to explain the phenomenon, giving rise to mythical explanations

2. In the 19th Century, Kristian Birkeland (1867-1917) was the first scientist to study thoroughly the aurora
   a. Compass needle deflections during the aurora hinted at an electromagnetic connection

   b. Birkeland used a "terrella" experiment — a miniature Earth in vacuum with a dipole magnetic field — to show that shining electron beams on it would create a glow reminiscent of the aurora.

3. In the 1950's, rockets provided direct access to space, pioneered by Prof. James Van Allen at the University of Iowa

   a. Carl McIlwain (1960), in his Ph.D. thesis at Iowa under Van Allen, published the first measurements that directly measured the electrons that cause the aurora.

II. A. (Continued)

3. (Continued)

b. McIlwain's measurements showed

i) Electrons were clearly non-Maxwellian

ii) Energies around 1–10 keV (poor energy resolution)

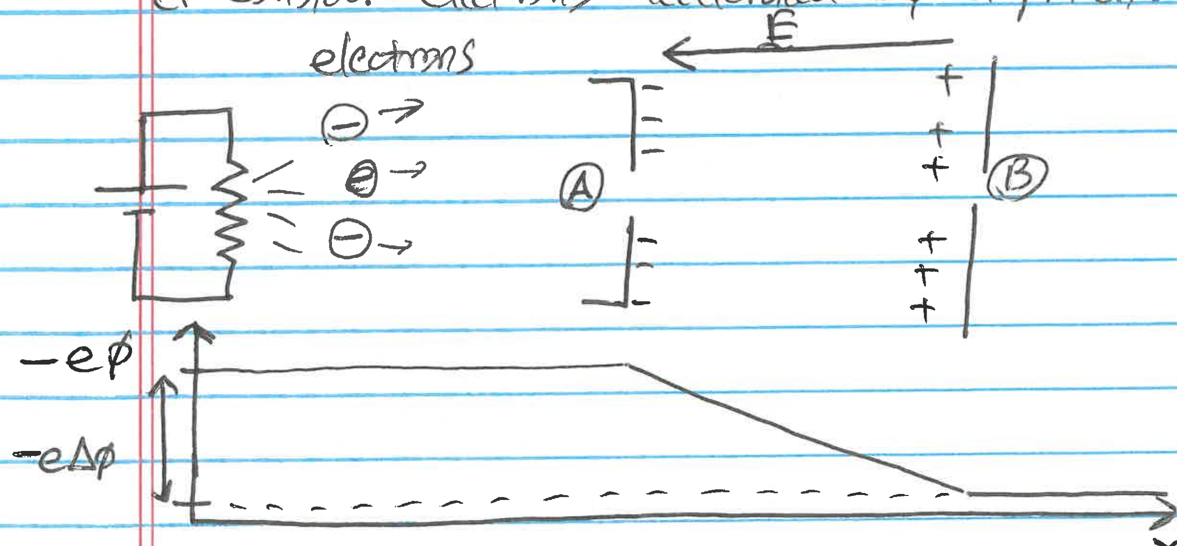
iii) Briefly suggested an electrostatic potential drop could explain observations

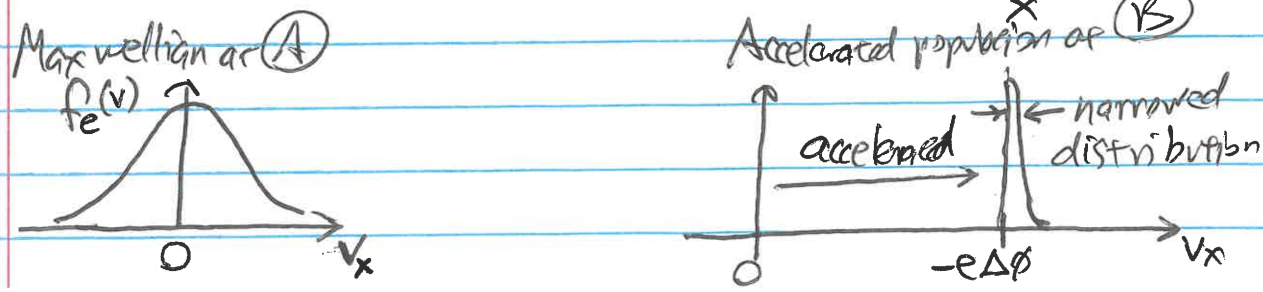
4. In the 1960's, measurements improved substantially

a. At approximately $z \sim 300$ km, Evans (1968) measured a relatively monoenergetic beam of electrons with an energy $E \sim 4$ keV

b. How is this consistent with an electrostatic potential along the magnetic field?

c. Consider electrons accelerated by a potential drop





II. A.4. (Continued)

d. The idea of a parallel electrostatic potential drop was fiercely resisted.

i) Why? The plasma is nearly collisionless, so $E_{\parallel}$ cannot be sustained

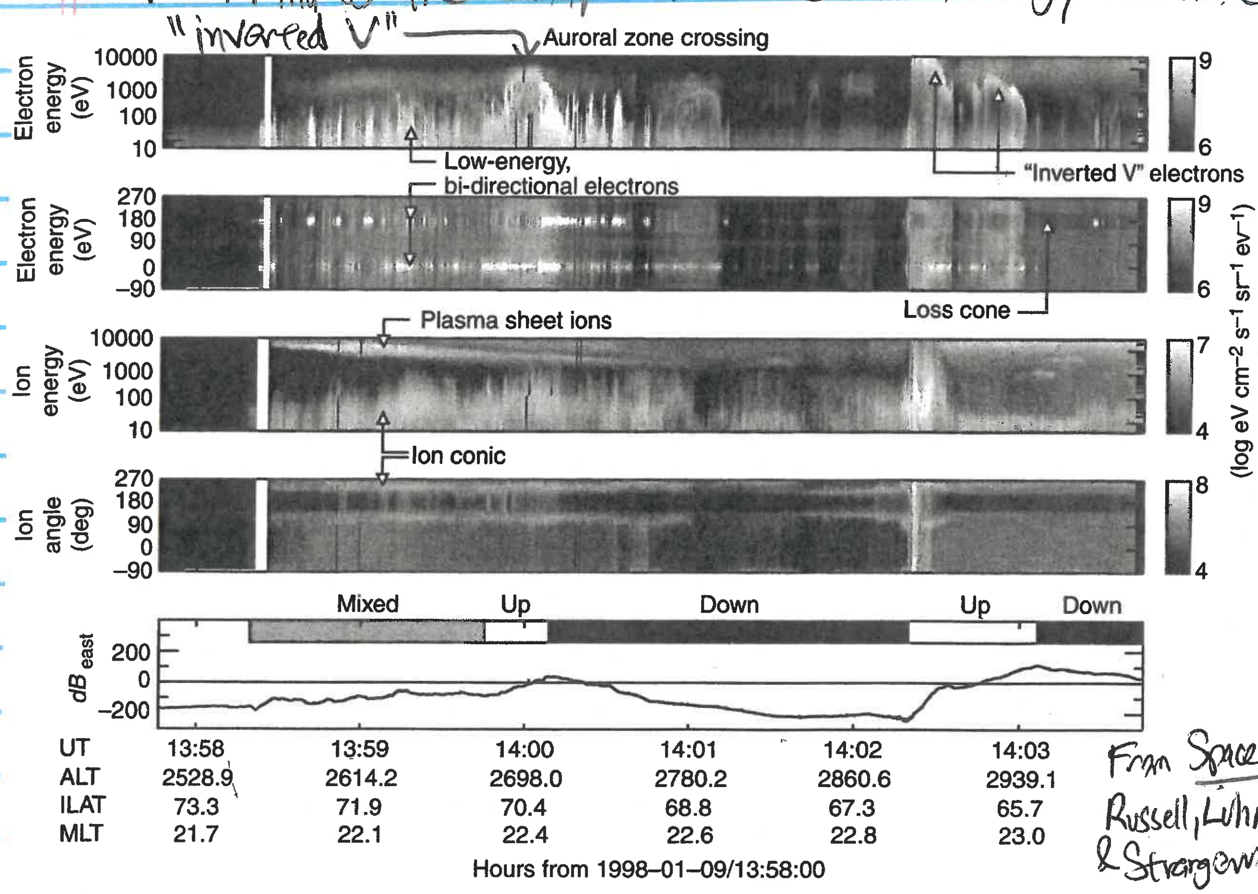
$$j_{\parallel} = \sigma_{\parallel} E_{\parallel} \quad \rightarrow E_{\parallel} = \frac{j_{\parallel}}{\sigma_{\parallel}}$$

($\sigma_{\parallel}$ ← parallel conductivity)

ii) But, for a collisionless plasma, $\sigma_{\parallel} \rightarrow \infty$, so $E_{\parallel} \rightarrow 0$!

5. The "Inverted V" term was coined by Frank & Ackerson (1971)

referring to the shape of the electron energy vs time plot.

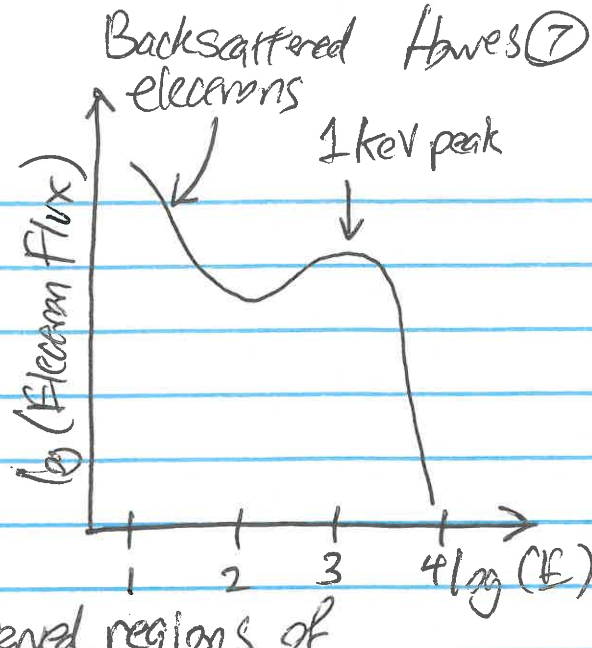


From Space Physics, Russell, Luhmann, & Strangeway (2016)

FIGURE 11.7. Observations of particles and fields taken by the Fast Auroral Snapshot (FAST) Small Explorer. The rectangles at the bottom of the figure show the different current regions, with white corresponding to upward current, black to downward current, and gray to a region of mixed upward and downward current.

II. A. (Continued)

6. Evans (1974) showed that backscattered precipitating electrons could fill in below the "mono-energetic" peak



7. Iijima & Potemra (1978) observed regions of upward & downward field-aligned currents.

IIJIMA AND POTEMRA: FIELD-ALIGNED CURRENTS DURING SUBSTORMS (1978)

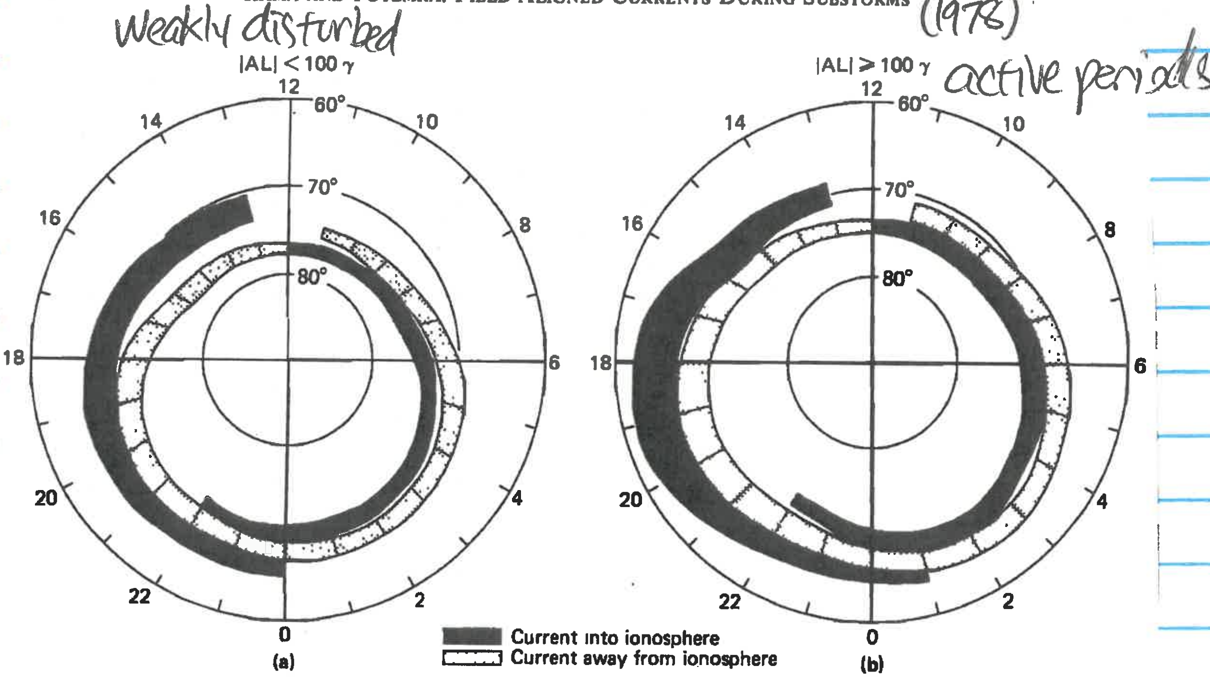


Fig. 13. A summary of the distribution and flow directions of large-scale field-aligned currents determined from (*a*) data obtained from 439 passes of Triad during weakly disturbed conditions ($|AL| < 100\ \gamma$) and (*b*) data obtained from 366 Triad passes during active periods ($|AL| \geq 100\ \gamma$).

8. In the 1980's, spacecraft measurements broke new ground

a. S3-3 spacecraft: first good electric field measurements ⇒ Quasi-static potential over range $800\,km \lesssim Z \lesssim 2000\,km$

b. DE-1 & DE-2 (1981)
c. Viking (1986)

] better particle measurements at higher time resolution

9. Mizera et al. (1982) used S3-3 electric field & particle measurements to infer potential structure of "inverted V."

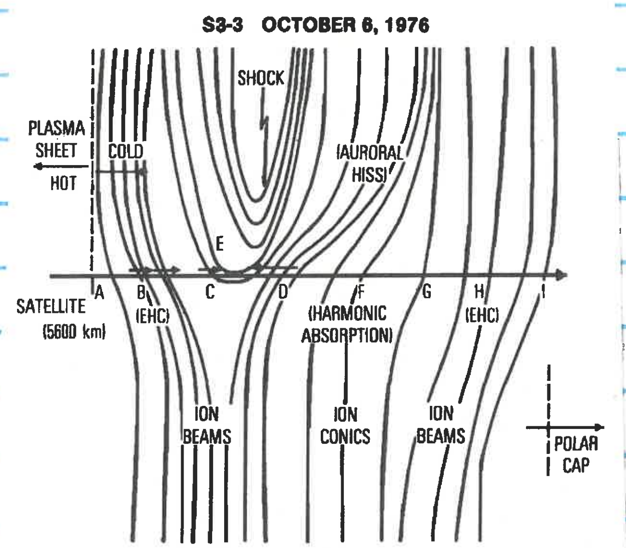
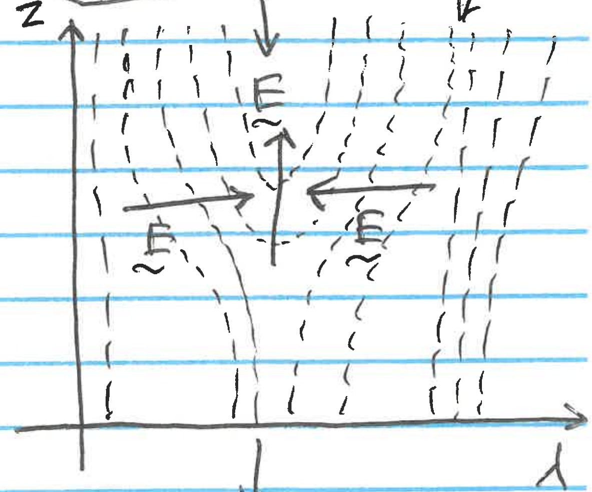


Fig. 4. Schematic drawing of potentials inferred from the charged particle distributions and electric fields for the late afternoon auroral pass on October 6, 1976. The satellite trajectory is illustrated by the heavy solid line, and the letters A–I are associated with events described in Table 1 and Figure 1.

Mizera et al. (1982)



10. In the 1990's, Freja (1992) and FAST (1996) missions provided ground-breaking new measurements

a. Freja: i) Downward current → upward electrons → "black" aurora
ii) Measurements motivated interest in Alfven waves!

b. FAST: Most complete set of measurements (Still the best auroral measurements) ⇓ TRACERS U Iowa!
i) Confirmed S3-3 picture of potential
ii) Upward electrons are a common feature
iii) Confirmed the role of Alfven waves

III. Theoretical Models of Auroral Dynamics

A. Early Studies focused on Quasi-static Potential Drop

1. Knight (1973) wrote a seminal paper on the field-parallel potential required to yield the observed field-aligned currents, though the origin of the potential remained unexplained.

2. Lundin & Sandahl (1978) extend the Knight results to be in terms of energy flux rather than current.

3. Swift (1976) proposed an electrostatic shock model to explain the potential drop

4. A number of other authors focused on explanations, such as anomalous resistivity, needed to justify the potential drop along the field line
   ⇒ this largely remains an open question.

B. Electron Acceleration by Alfvén Waves

1. Hasegawa (1976) first proposed that kinetic effects could generate field-parallel electric fields needed.

2. Goertz & Boswell (1979) showed the "inertial Alfvén wave" has a significant parallel electric field at small perpendicular wavelengths.

III. B. (Continued)

2. (Continued) → Inertial Alfvén Waves

a. Frequency: $\omega = \frac{k_\parallel V_A}{\sqrt{1+(k_\perp \delta_e)^2}}$ ← electron inertia slows down the Alfvén wave

b. Parallel Electric Field: $E_\parallel = E_\perp \frac{(k_\parallel \delta_e)(k_\perp \delta_e)}{1+(k_\perp \delta_e)^2}$

c. Plasma Skin Depth $\delta_e = \frac{c}{\omega_{pe}}$

d. Expression is valid for very low plasma beta

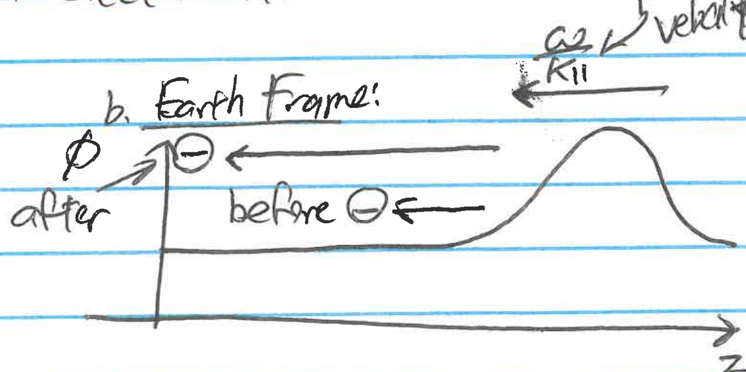
$$\beta_i < \frac{m_e}{m_i} \sim 10^{-3}$$

3. Lysak (1983, 1985, 1986) developed a series of papers connecting inertial Alfvén waves to potential drops.

4. Kletzing (1994) showed that Earthward propagating Alfvén waves could accelerate electrons in a single-bounce Fermi acceleration.

a. Wave Frame:

b. Earth Frame:



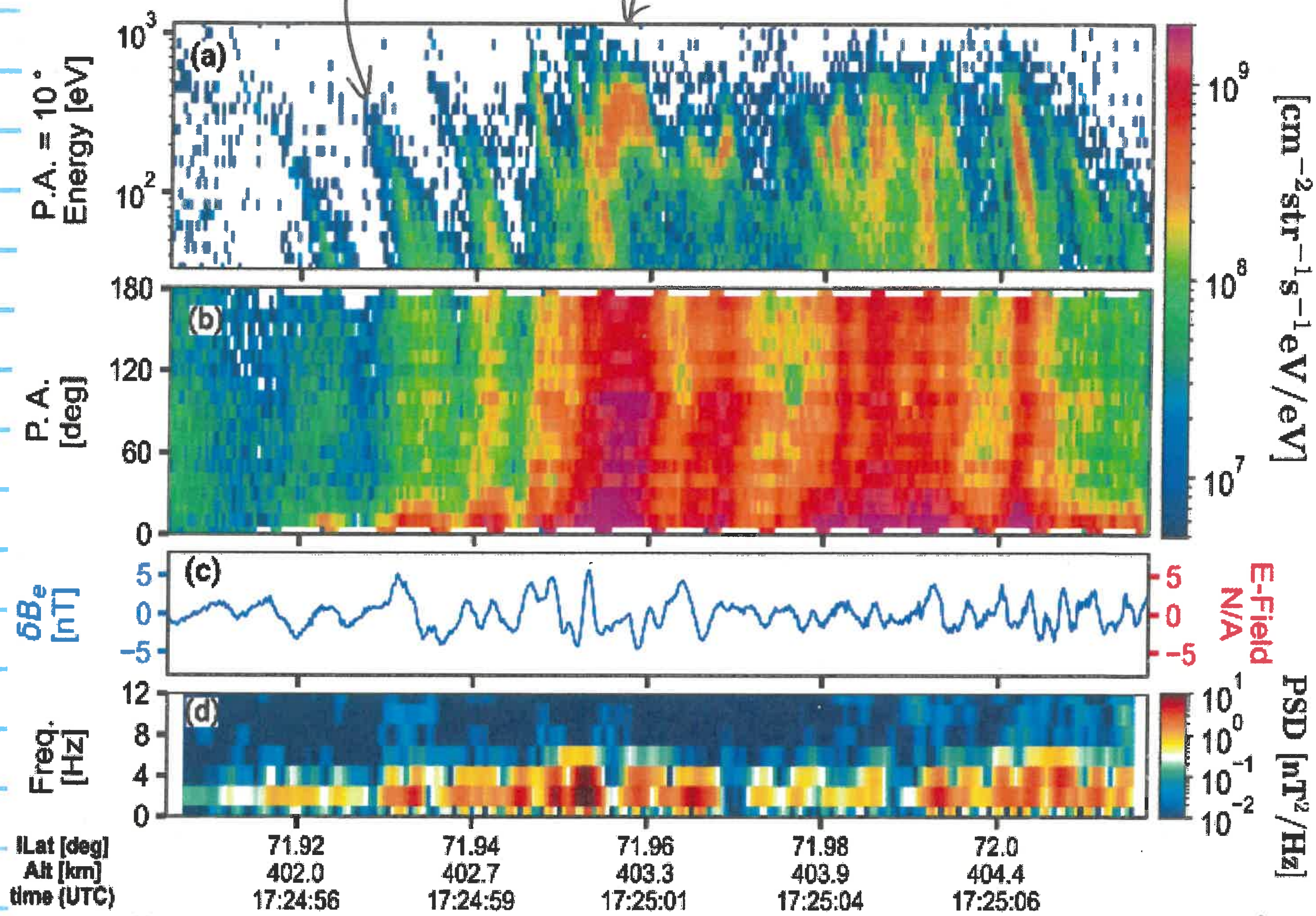
5. Kletzing & Hu (2001) showed Alfven wave acceleration explains observed signatures of electron time dispersion.

III.B. (Continued)

6. ACES-II sounding rocket measurements at z ~ 400 km

Time-dispersed electron signatures

inverted V



Connor Feltman, U Iowa Ph.D. Thesis (2024)

III. (Continued)

Howes (13)

C. Verification of Alfven-Wave-Acceleration in Lab Experiments

1. Schroeder, Howes, Kletzing, Skiff, Carter, Vincena, & Dorfman, Nat Comm. (2021), a U Iowa-UCLA collaboration, conducted laboratory experiments to demonstrate the Alfvén wave acceleration of electrons under the conditions of the auroral magnetosphere.

electrons in the suprathermal tail of the velocity distribution are accelerated by inertial Alfvén waves

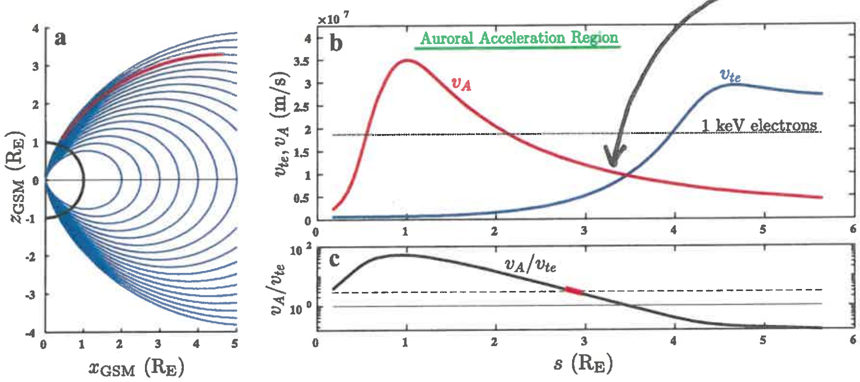
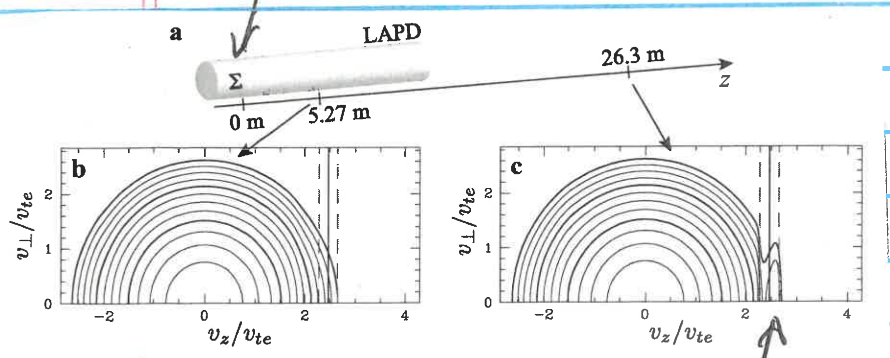
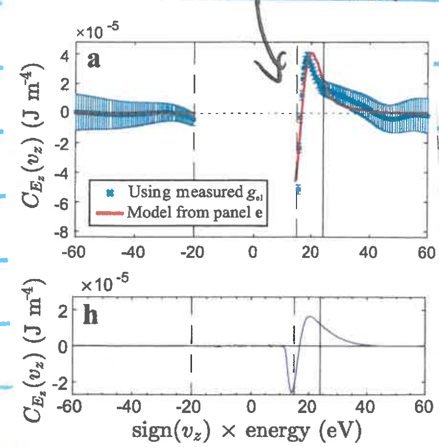


Fig. 5 Model of the auroral zone. a Plot of the Earth's dipole magnetic field lines (blue) and the segment (red) along the field line through the auroral acceleration region for $L = 8.5$ (or invariant latitude $\Lambda = 70°$). Profiles of (**b**) the Alfvén speed v_A (red) and electron thermal velocity v_{te} (blue) as well as (**c**) their ratio v_A/v_{te} (black) as a function of distance along the field line s. The dashed line shows the ratio $v_A/v_{te} \simeq 3$ relevant to the LAPD experiments reported here. The highlighted red region shows the experimental v_A/v_{te} corresponds to v_A/v_{te} in the auroral zone near a distance s of 3 R_E.

inertial Alfven waves launched here

Field-particle correlation technique confirms resonant acceleration





Predicted bump of accelerated electrons

IV. Open Questions in Auroral Physics

A. For Quasi-static potentials (inverted V)

1. How is the potential distributed along the field line? How is it supported? — No good models.

2. How do quasi-static auroral arcs evolve? Are they started by Alfven waves, or some other mechanism?

3. Is the system current or voltage driven?

4. Which processes in the plasma sheet drive the aurora?