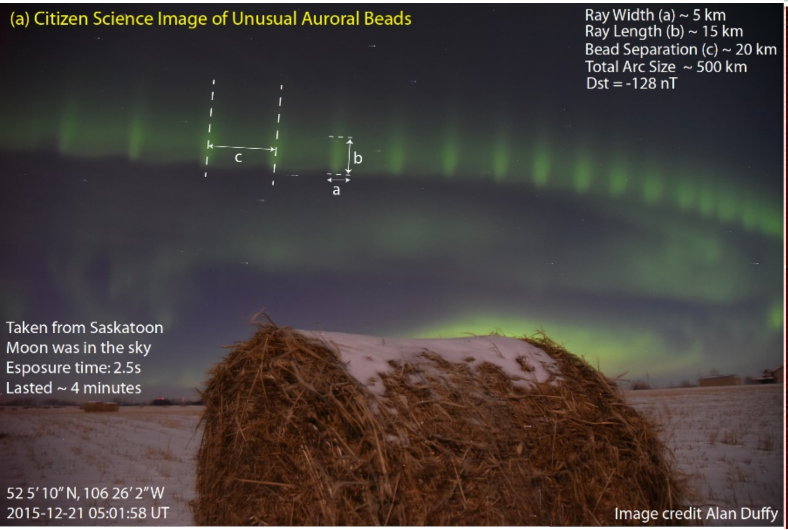
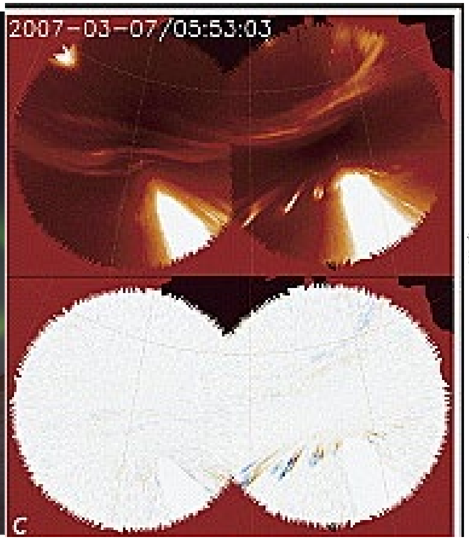
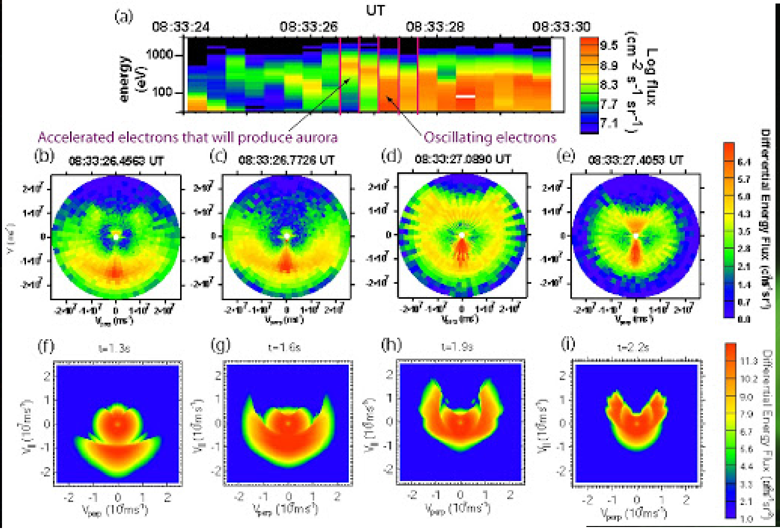
Auroral Acceleration Mechanisms and how they relate to the Magnetospheric Substorm

Prof Clare E. J. Watt, Northumbria University, Newcastle upon Tyne, UK





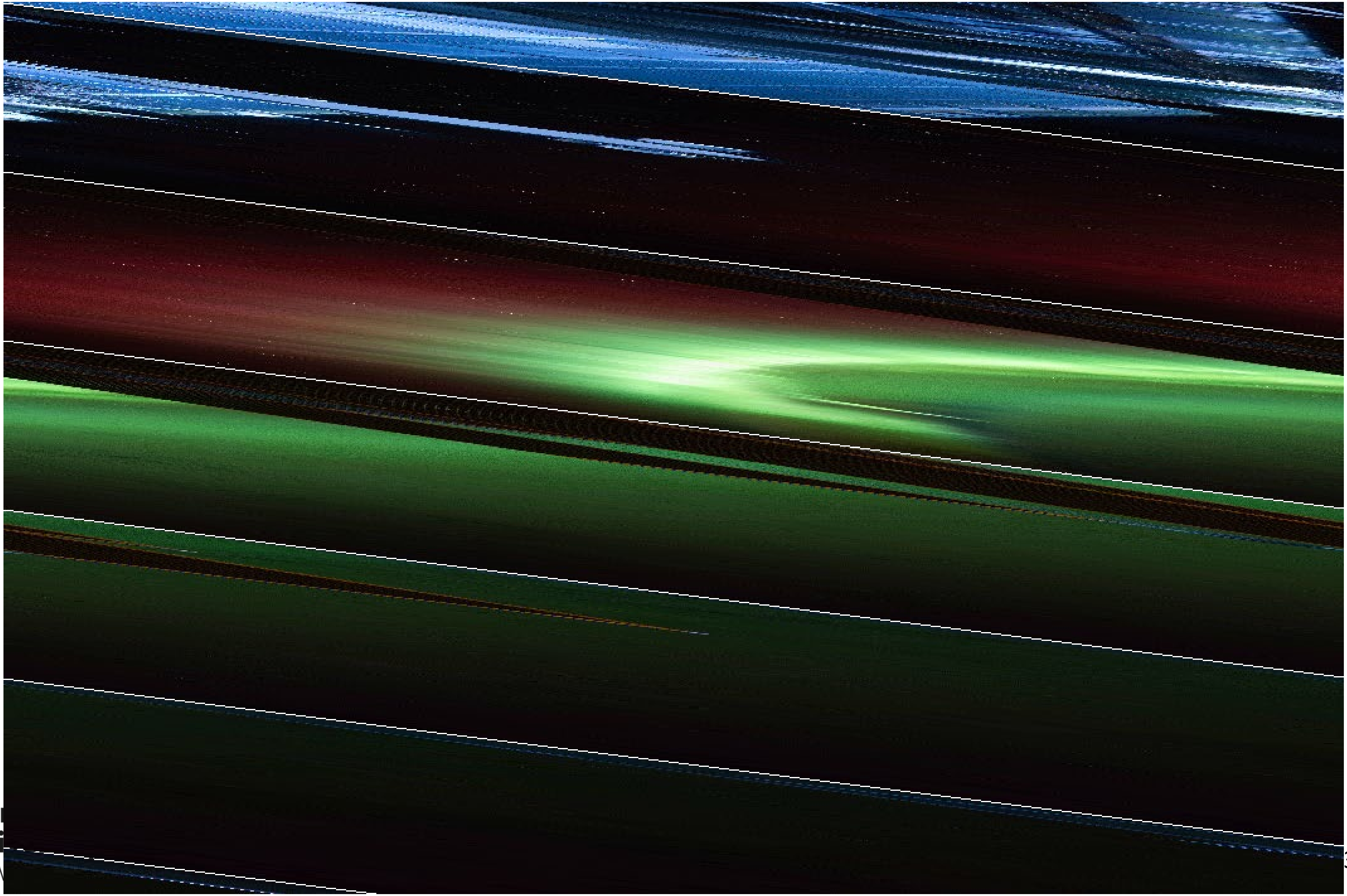


With thanks to…

Jonathan Rae, Nadine Kalmoni, Kyle Murphy, Robert Rankin, Colin Forsyth, Andy Smith, John Samson, Gordon Rostoker, Bob Lysak, David Knudsen

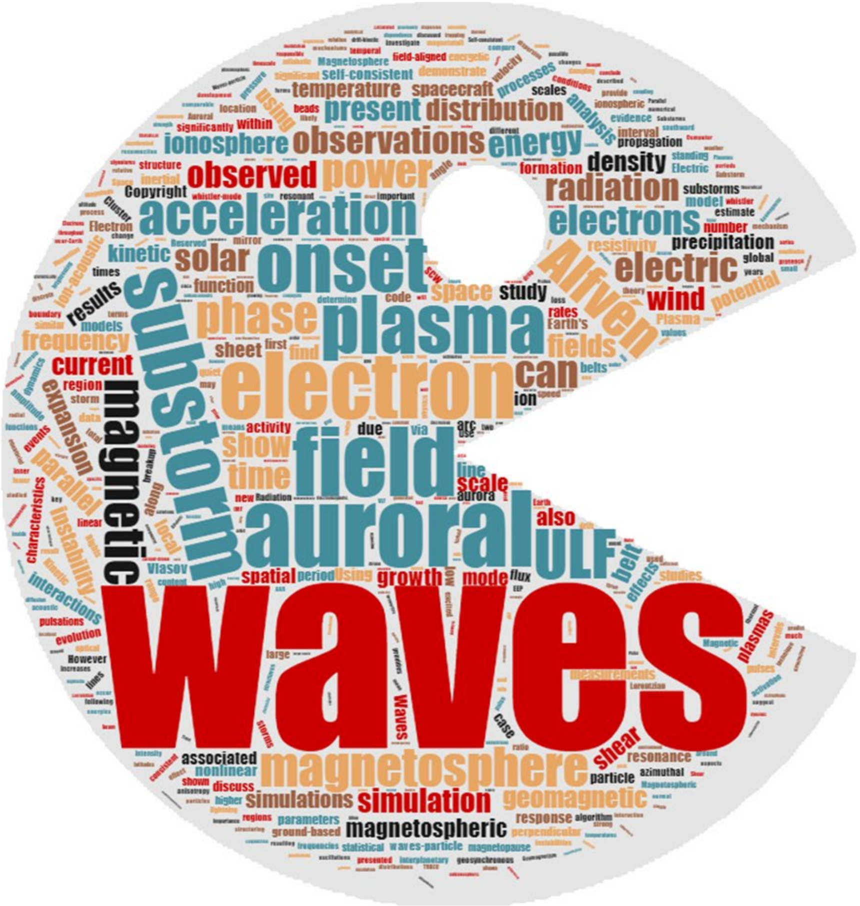
NASA FAST mission team, NASA THEMIS mission team, CSA Canadian GeoSpace Monitoring ground-based teams (Geospace Observatory Canada), ESA Cluster mission team, CSA e-POP mission team

Disclaimer – references are *not exhaustive*!!



Auroral physics through my own biases

- I spent 11 years at University of Alberta (2002-2013)
  - ULF waves, substorms, field-line resonances
  - Rankin, Samson, Mann, Rostoker, Rae, Murphy, Kabin, Ozeke, Usanova, Fenrich, Degeling, Miles, Milling and many others
- Auroral physics from the perspective of someone obsessed with waves and wave-particle interactions



From my abstracts 2002-2015

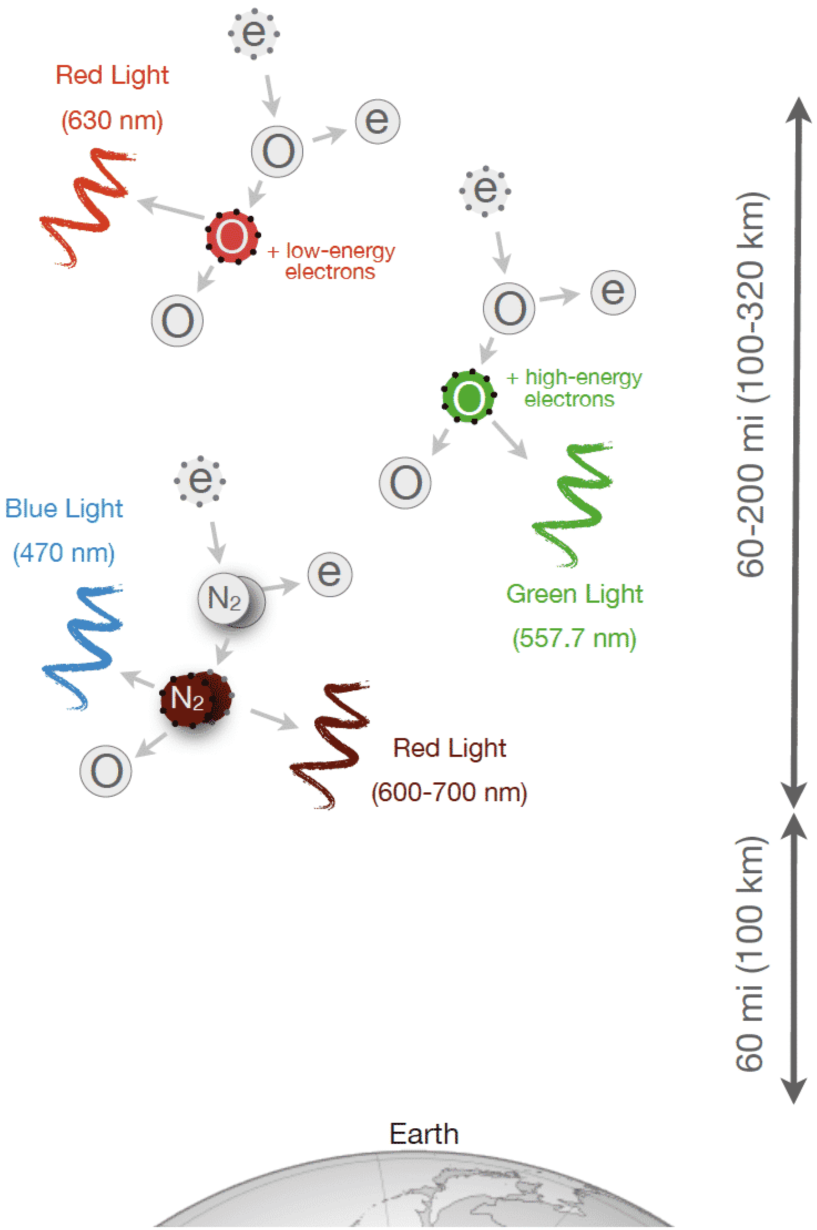
Summary

1. Fundamental Auroral Physics
2. Auroral Morphology
3. Auroral Acceleration Mechanisms
4. Auroral Acceleration near Substorm Onset
5. Thoughts on the future

1. Fundamental Auroral Physics

Light from Aurora

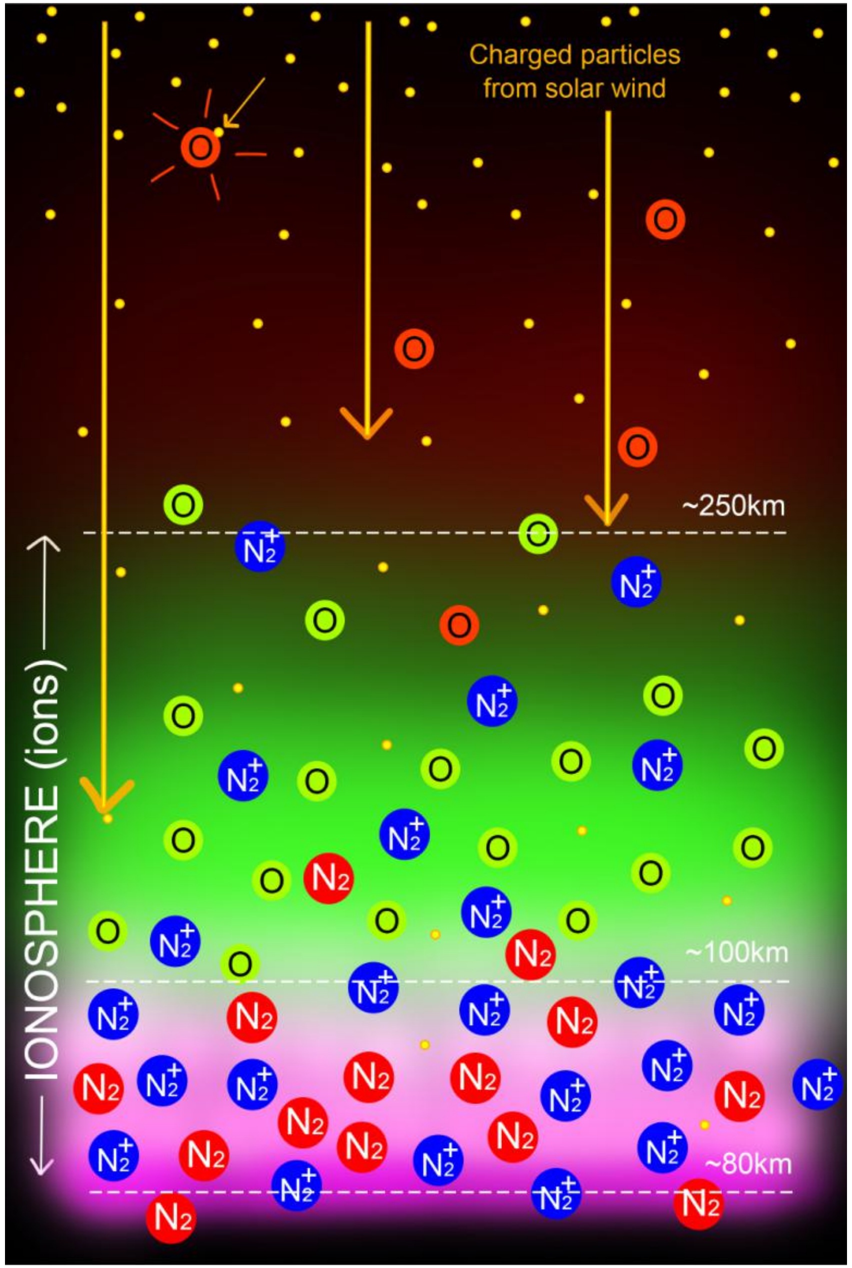
- Auroral displays result from collisions
- Energetic electrons and protons from space collide with
  - Neutral atoms (O)
  - Neutral molecules (N_2)
- Collisions → Excitation of neutrals
- Decay → Emission



https://www.alaskaphotographics.com/

Different Colours from Different heights

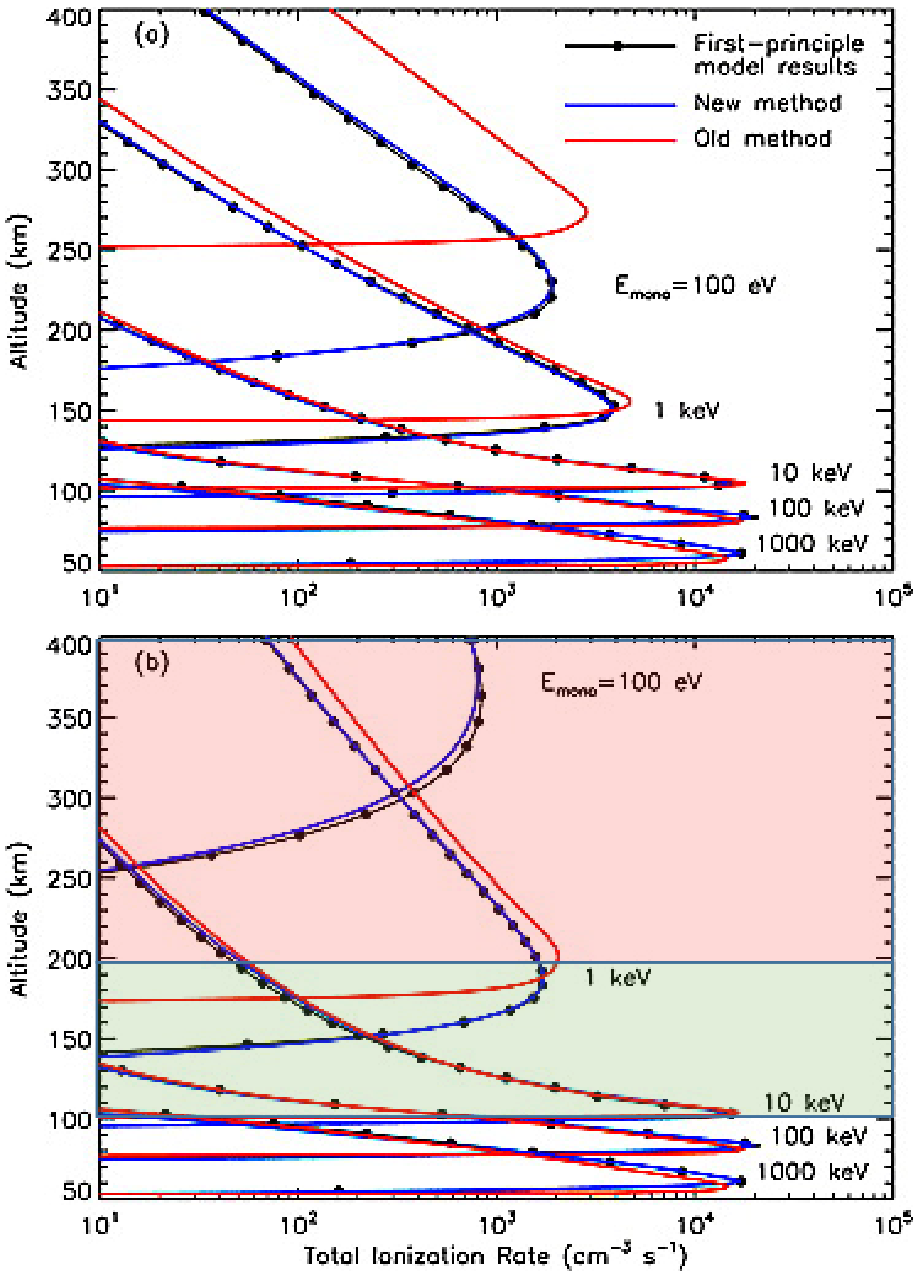
- Collisions with atmospheric constituents change with height
  - Oxygen atoms more prevalent at higher altitudes
  - Nitrogen molecules more prevalent at lower altitudes



aurorabborealisobservatory.com

Different energies reach different heights

- Higher energy electrons reach lower altitudes before losing energy due to collisions
- Altitude of collisions also depends on thermosphere/ionosphere
  - Panels (a) and (b) have different thermosphere/ionosphere parameters
  - Mainly affects lower energies
- Don't forget "secondaries" – high-energy electrons that have had collisions but still have sufficient energy to excite atoms



Fang et al., GRL [2010]

Aurora as a remote-sensing tool

- My interest in aurora is how they provide a 2D *ionospheric* window into processes that are either/both:

- *magnetosphere-ionosphere* coupling
- intrinsically *magnetospheric*

National Institute of Polar Research, Japan

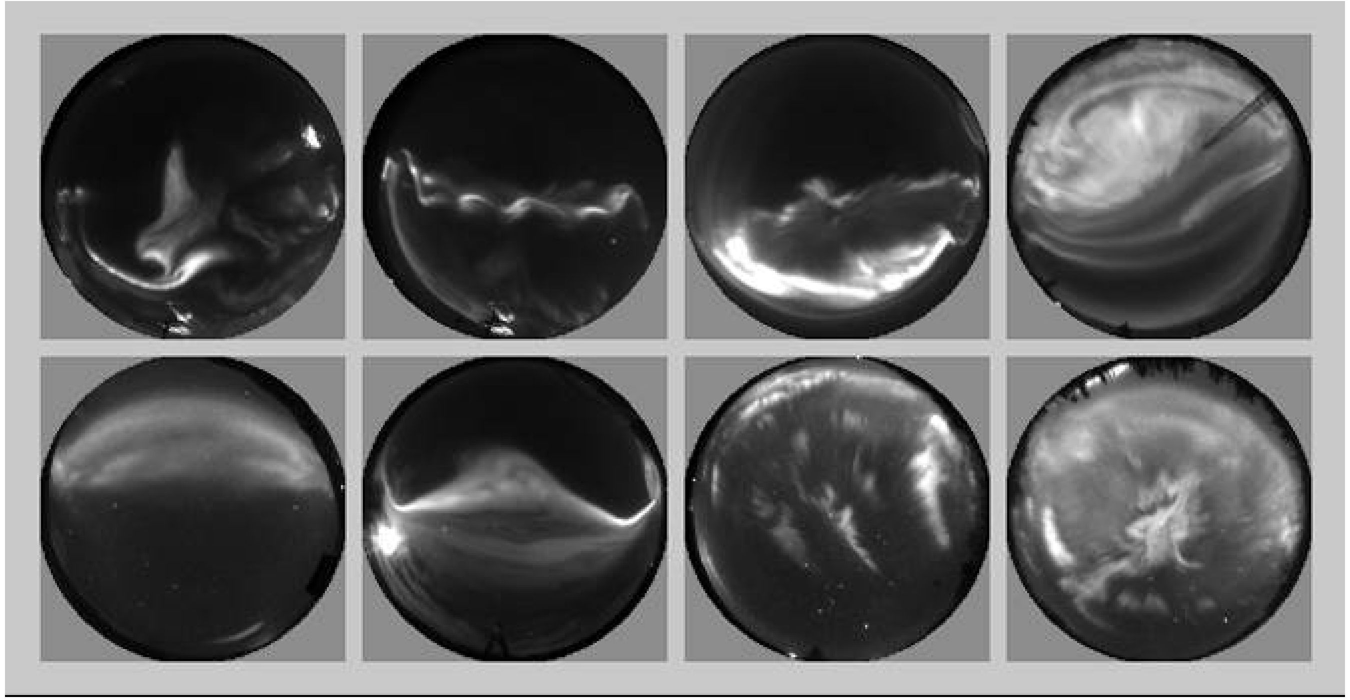
http://pc115.seg20.nipr.ac.jp/www/opt/index.html

This talk is about electron precipitation that causes the aurora

2. Auroral Morphology

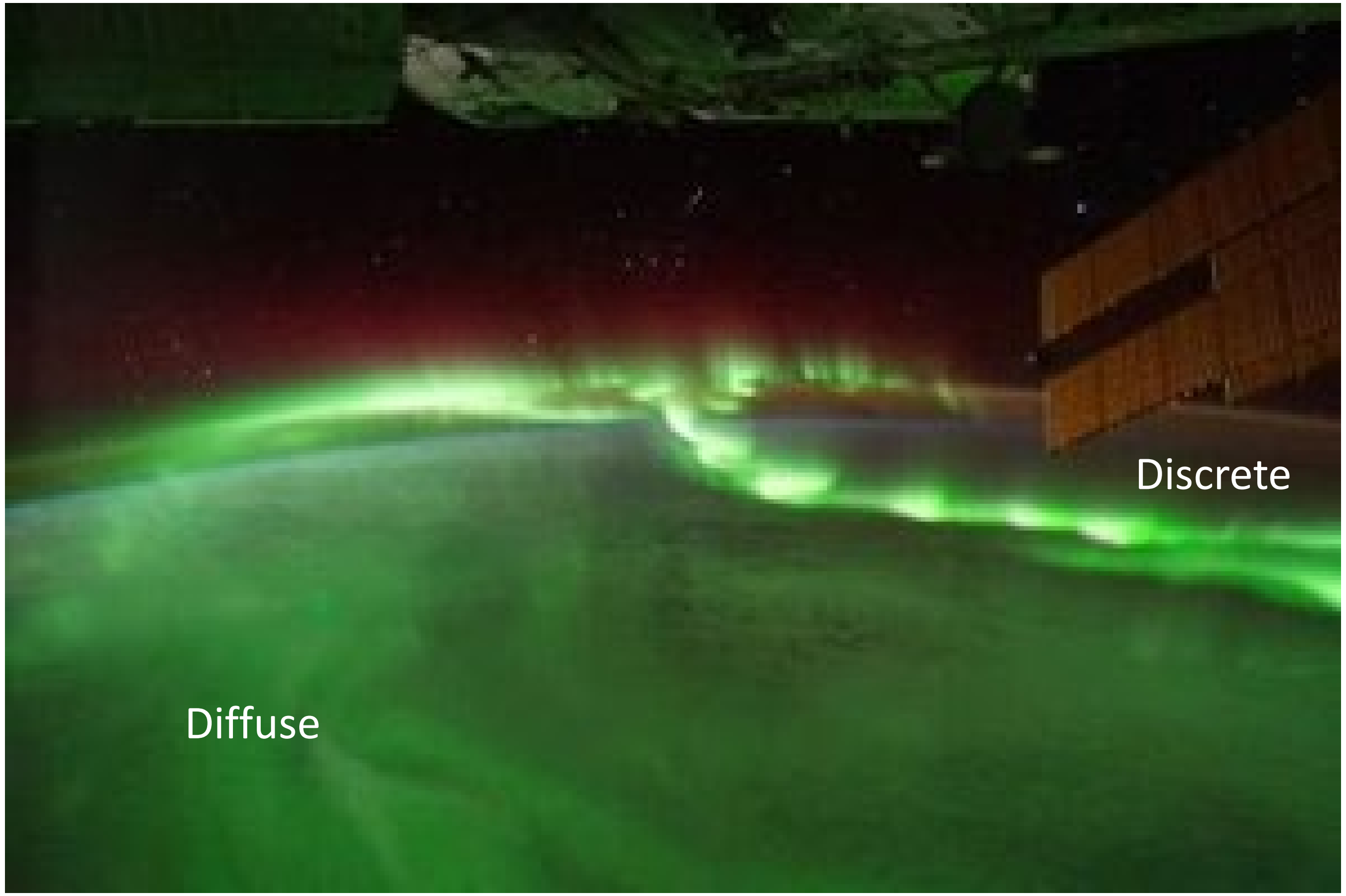
Morphology of Aurora

- Arcs
- Field-line resonances
- Polar cap aurora
- Patchy aurora
- Pulsating and flickering aurora
- Substorm aurora



Examples of All-Sky Imager (ASI) data from NASA THEMIS ground-based segment

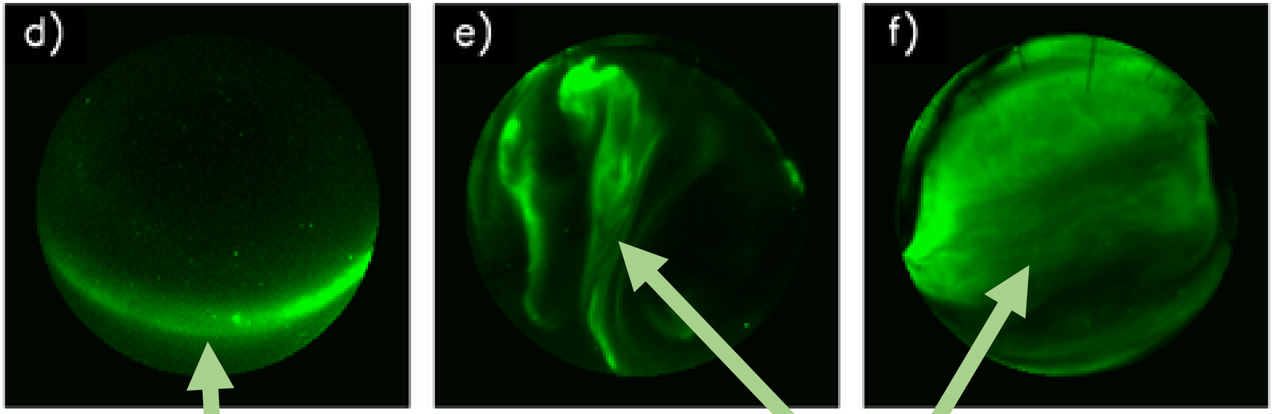
Discrete vs Diffuse



Auroral Arcs

- “Classic” discrete auroral shape
- Observed throughout auroral oval
- Often relatively stationary
- Elongated in East-West direction (horizon-to-horizon)
- Narrow in North-South direction

Auroral arc from Shetland, www.davegifford.co.uk



Clausen and Nickisch, JGR [2018]

Arc

Not arcs

Auroral Arc Physics

- Acceleration Region
  - Related to “quasi-stationary” acceleration mechanisms
  - Must be narrow in N-S direction
  - Often green, so >1keV electrons necessary

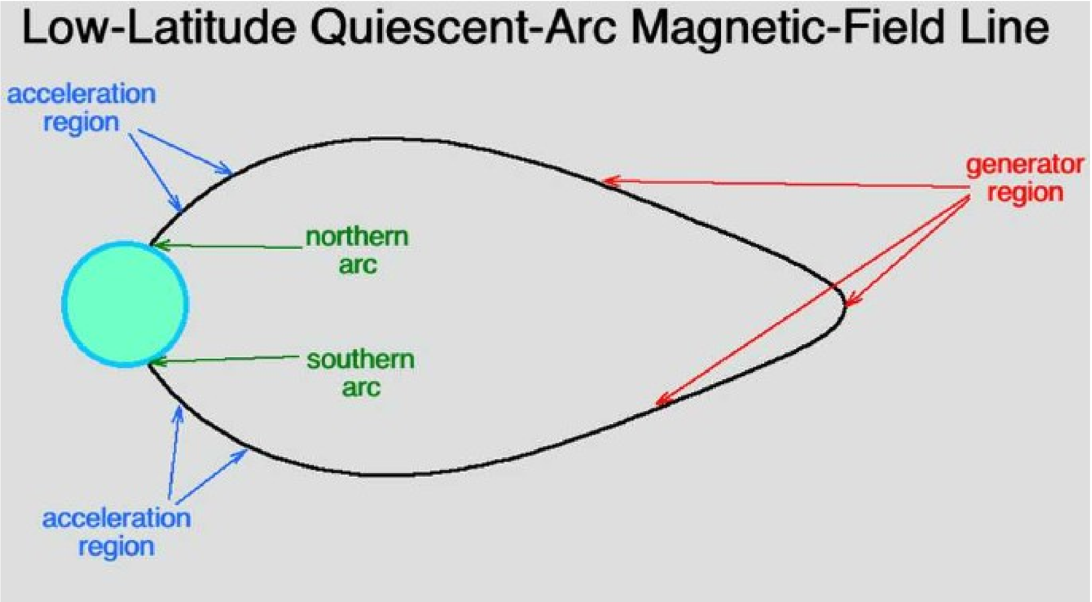


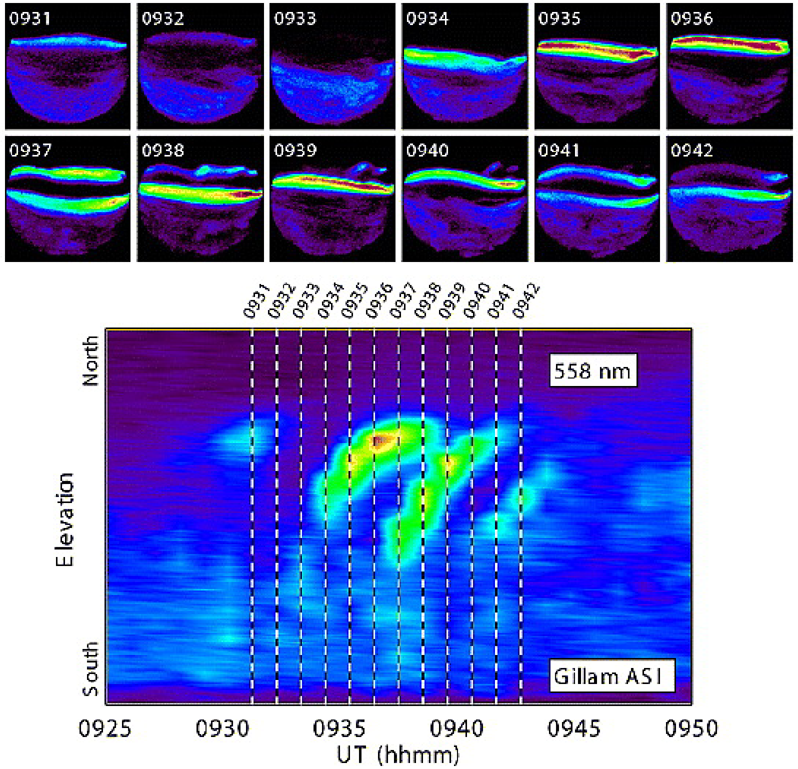
Figure 1, Borovsky et al., [2020]

- Reviews
  - *Borovsky et al., SSR [2020]*
  - *Paschmann et al., SSR [2002]*
  - *Lysak et al., SSR [2020]*

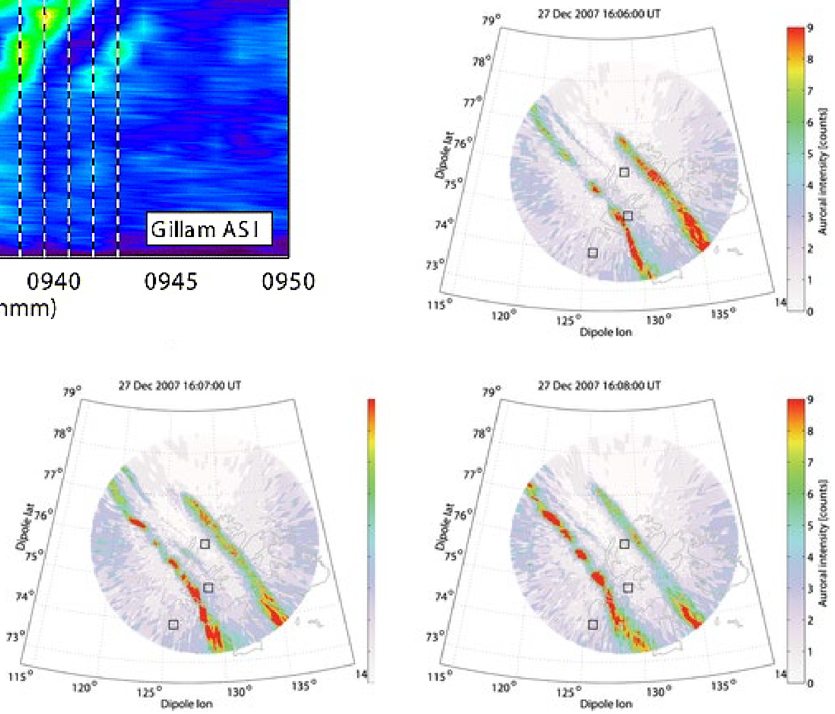
- High-latitude arcs may map to Plasma Sheet Boundary Layer/Low Latitude Boundary Layer
  - *Echim et al., GRL [2009]*
- Low-latitude arcs related to pressure gradients or stationary Alfvén waves
  - *Haerendel, JGR [2011]*
  - *Knudsen, JGR [1996]*

Field-line resonance

- A series of discrete arcs
- Arcs move slowly polewards or equatorwards
- Then replaced by another arc
- Manifestation of field line resonance in magnetosphere
    - *Samson et al., JGR [1996]*
    - *Damiano et al., GRL [2018]*
    - *Rae et al., JGR [2019]*

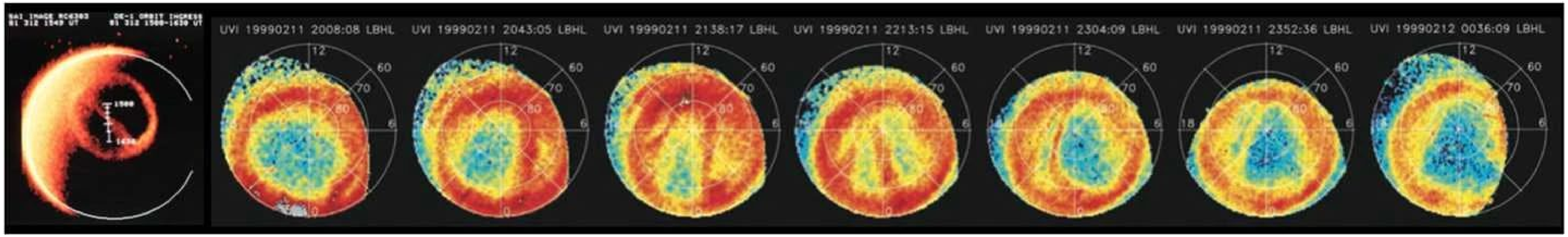


Rankin et al., JGR [2005]



Baddeley et al., JGR [2017]

Polar cap aurora (transpolar arcs)

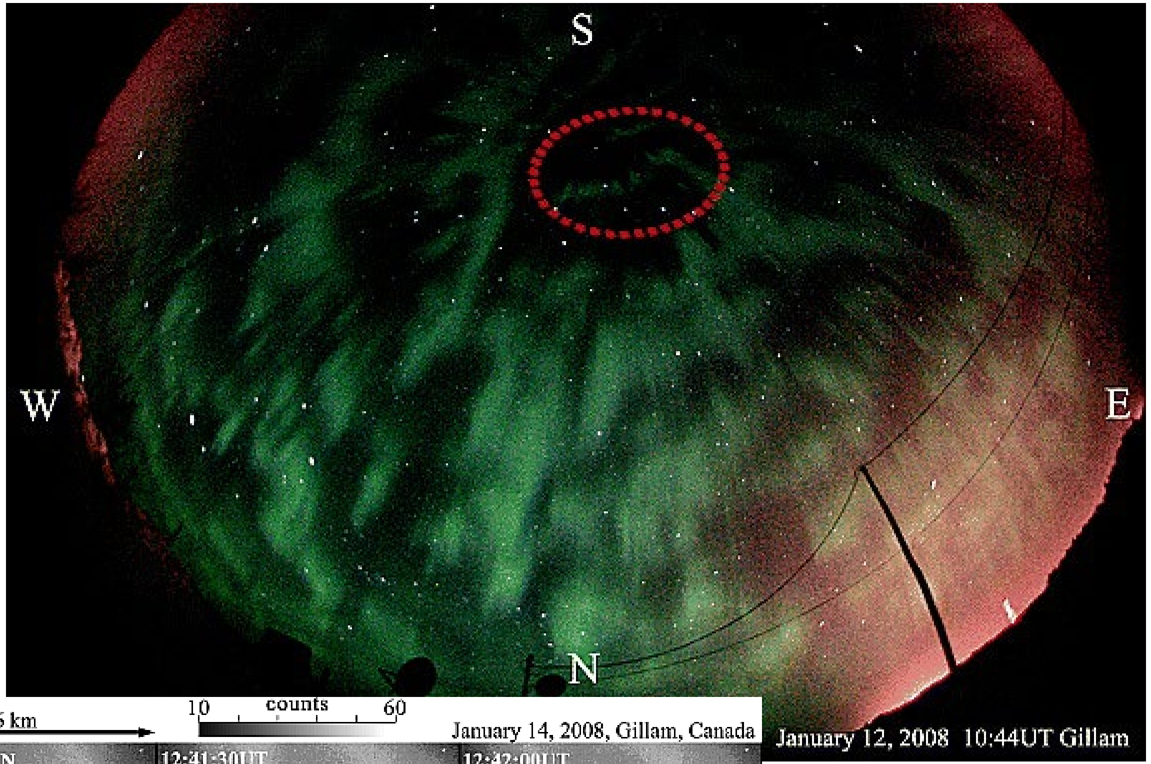


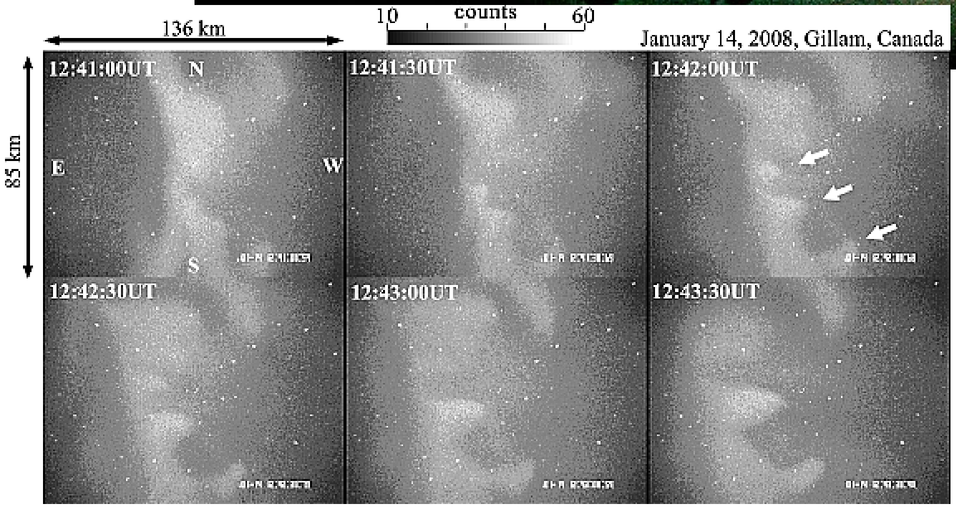
Kullen et al., JGR [2002]

- Also known as “theta aurora”
- Large scale features, best appreciated from space
- Predominantly occur during northward IMF periods, with strong +Bz and high solar wind speed
- Review – *Hosokawa et al., SSR [2020]*

Patchy aurora

- Irregular-sized patches
- Can appear to glow, then abruptly stop, then abruptly start again
- Often a post-midnight phenomenon
- Diffuse aurora, although there are features on a range of scales

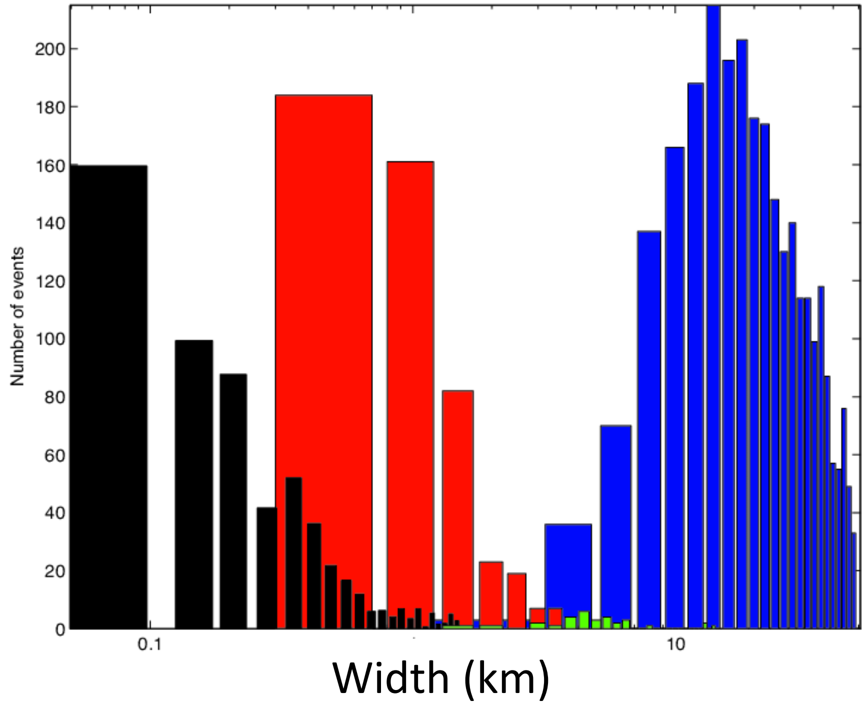




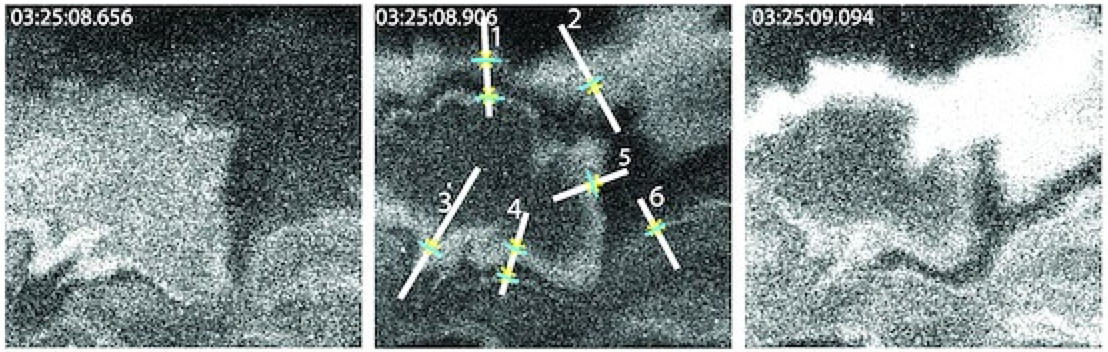
Shiokawa et al., JGR [2010]

Look at aurora more and more closely, you will see more and more structure

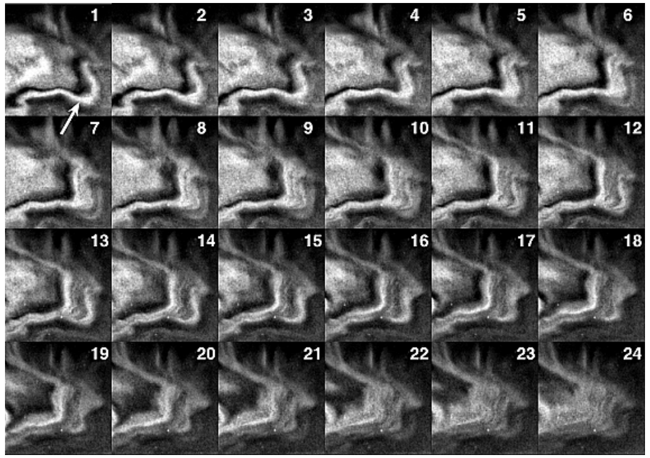
Width of auroral arcs when viewed in different cameras



Partamies et al., AG [2010]



Dahlgren et al., GRL [2012]

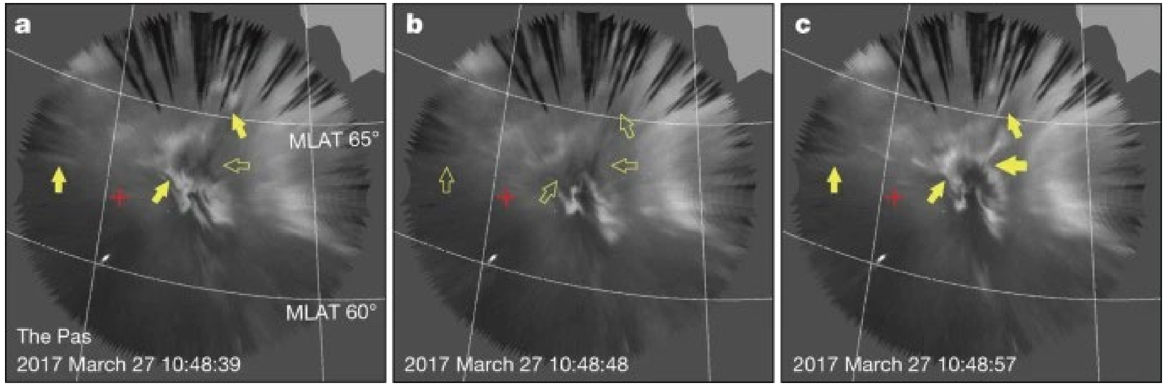


Semeter and Blixt, GRL [2006]

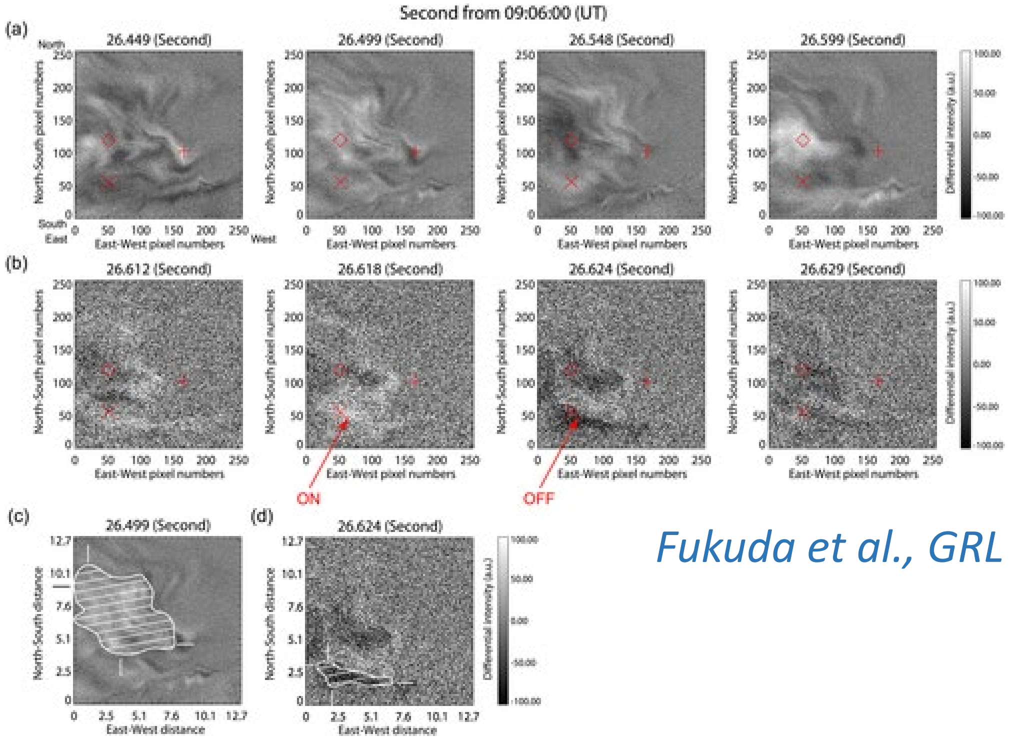
Pulsating and Flickering aurora

- Auroral forms that change brightness regularly
- Related to patchy diffuse aurora
- Pulsating aurora has periods ~ 2-20s and spatial structure 10-200km
- Flickering aurora has periods < 0.1s

- Pulsating aurora review
  - *Nishimura et al., SSR [2020]*



Kasahara et al, Nature [2018]



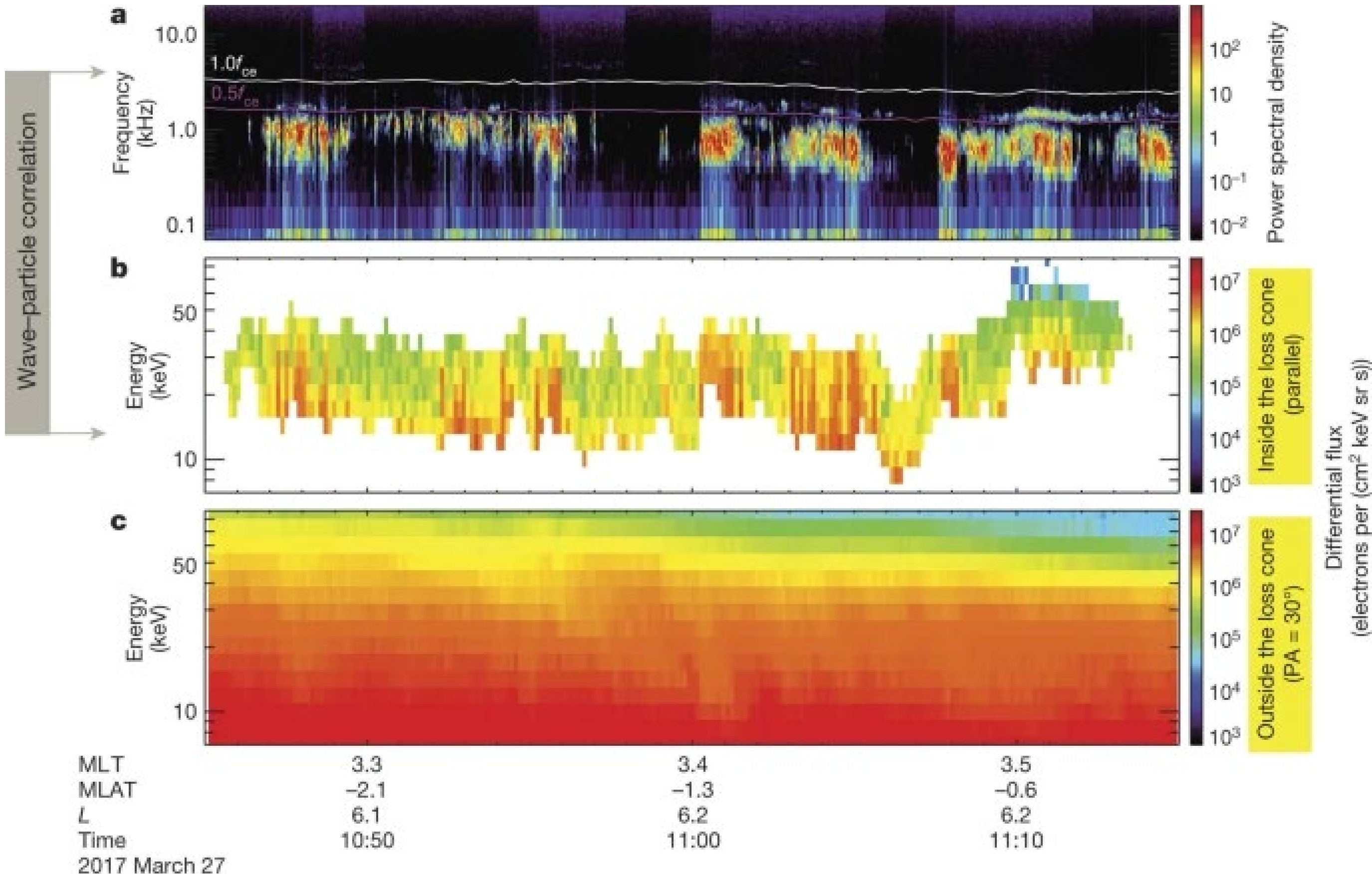
Fukuda et al., GRL [2017]

Pulsating aurora

ERG/Arase s/c

- Physical mechanism most likely related to wave-particle interactions in magnetosphere

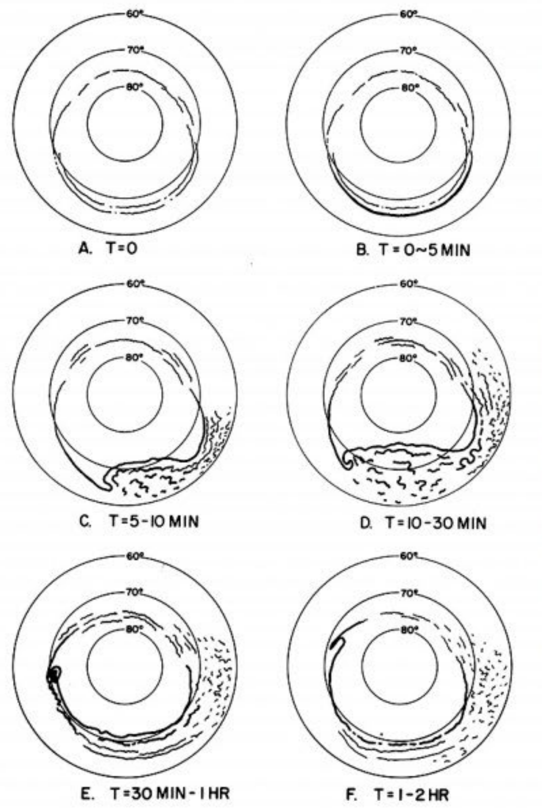
- Pulsating aurora – chorus waves
  - *Nishimura et al., Science [2010]*
  - *Kasahara et al., Nature [2018]*
  - *Ozaki et al., Nature Comms [2019]*
- Flickering aurora – EMIC waves?
  - *Fukuda et al., GRL [2017]*

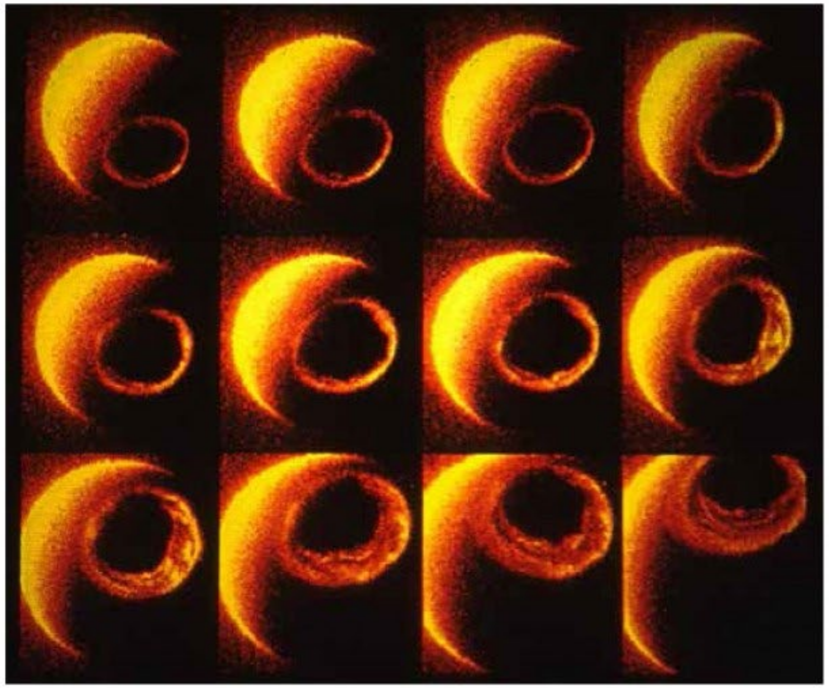


Kasahara et al, Nature [2018]

Substorm aurora

- Substorms originally defined by auroral activity *[Akasofu, P&SS, 1964]*
  - Sudden brightening of aurora
  - Rapid apparent motion polewards
  - Auroral display then fills the sky showing complex patterns





Akasofu, EOS [2015]

Substorm aurora – more recent developments

- More recent studies shows prevalence of azimuthal structure in auroral arc in 5 minutes surrounding onset
- >90% of events

Rae et al., JGR [2009]

Kalmoni et al., JGR [2015]

Kalmoni et al., Nature Comms [2018]

Substorm onset independently identified from SuperMAG ground-magnetometer data

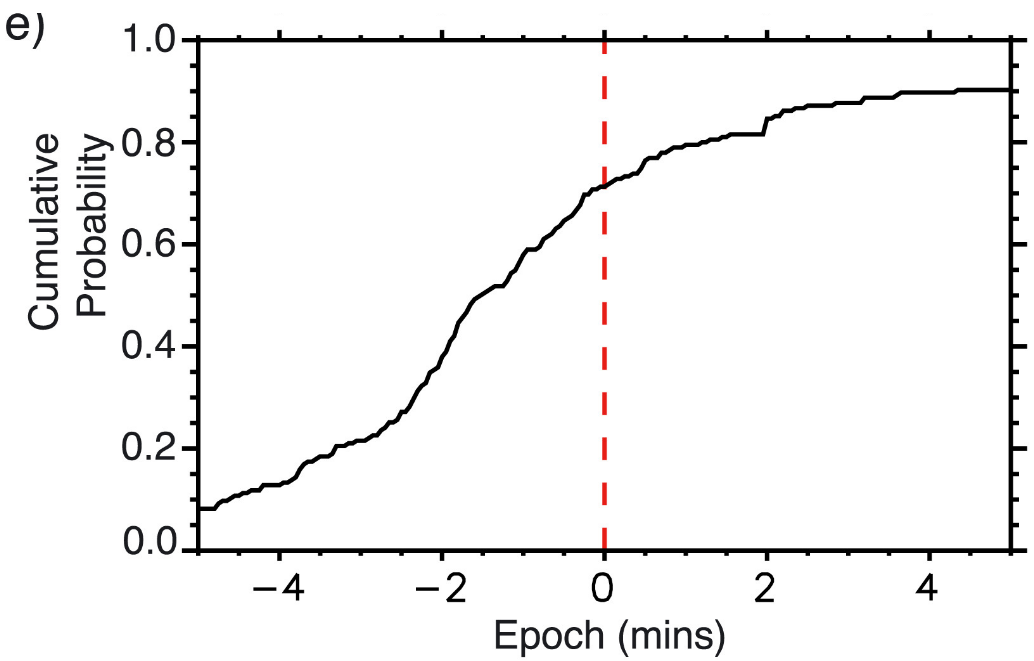


Figure 2, Kalmoni et al., GRL [2017]

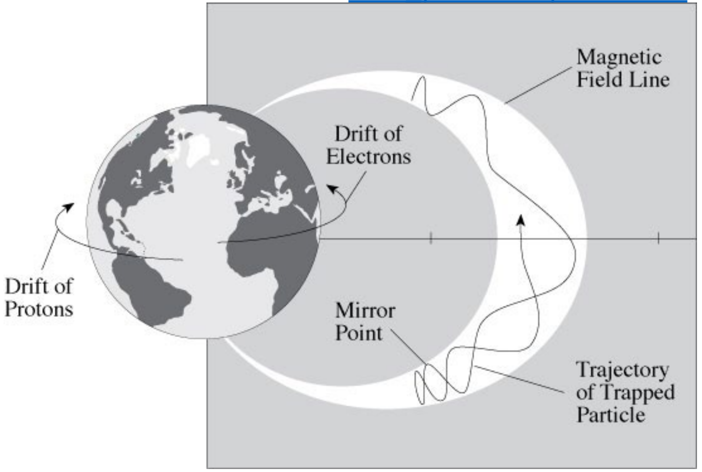
3. Auroral Acceleration Mechanisms

Entry into the loss-cone

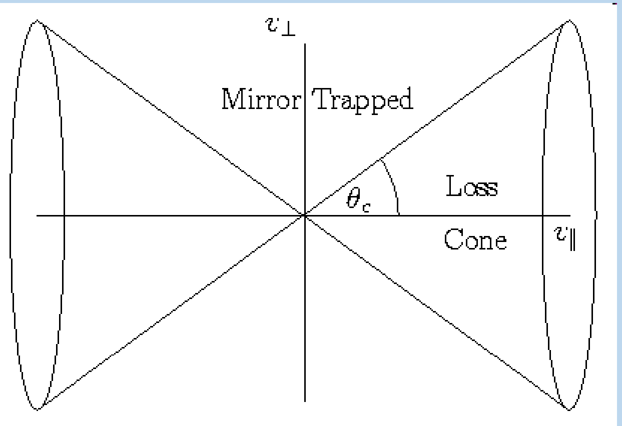
- Magnetospheric electrons are usually trapped
- Electrons bounce from one hemisphere to another due to mirror force in closed magnetospheric field

- To precipitate and cause aurora, they must be moved into loss cone

Prof K. Lang, Tufts University: [*https://ase.tufts.edu/cosmos/view_picture.asp?id=1000*](https://ase.tufts.edu/cosmos/view_picture.asp?id=1000)



3D



2D

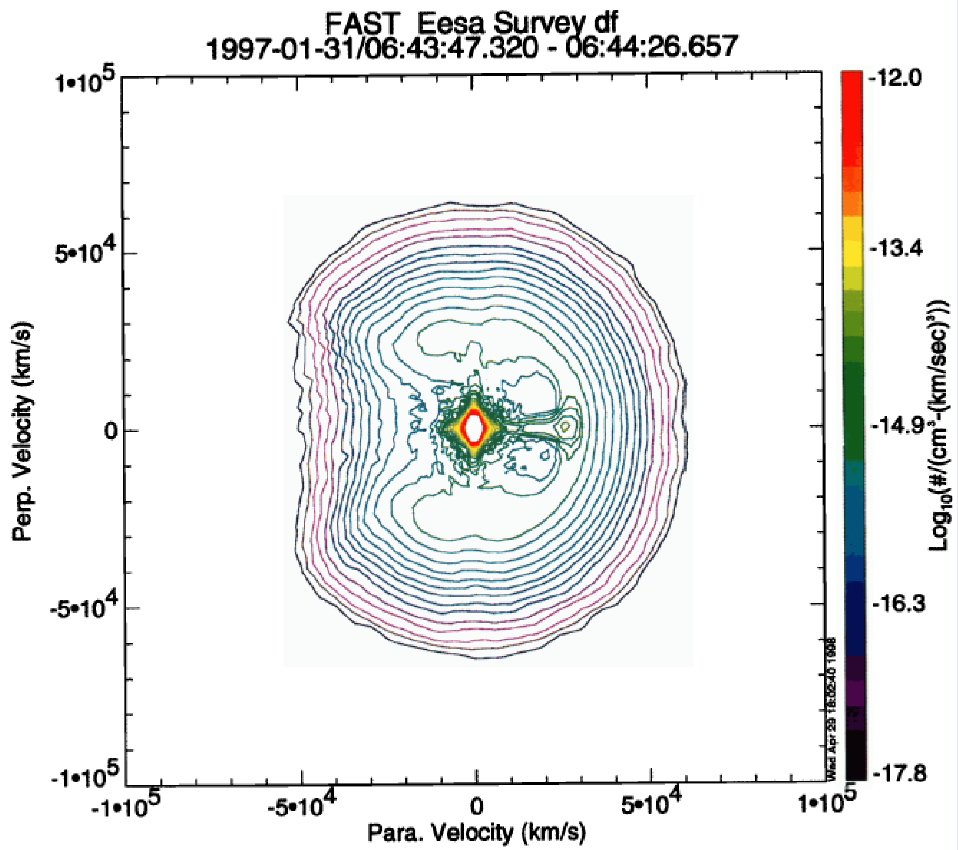


Plate 1. Electron contour plots in $v_\parallel, v_\perp$ space from a FAST crossing of the AKR source region on orbit 1761.

Delory et al., GRL [1998]

Northumbria University NEWCASTLE

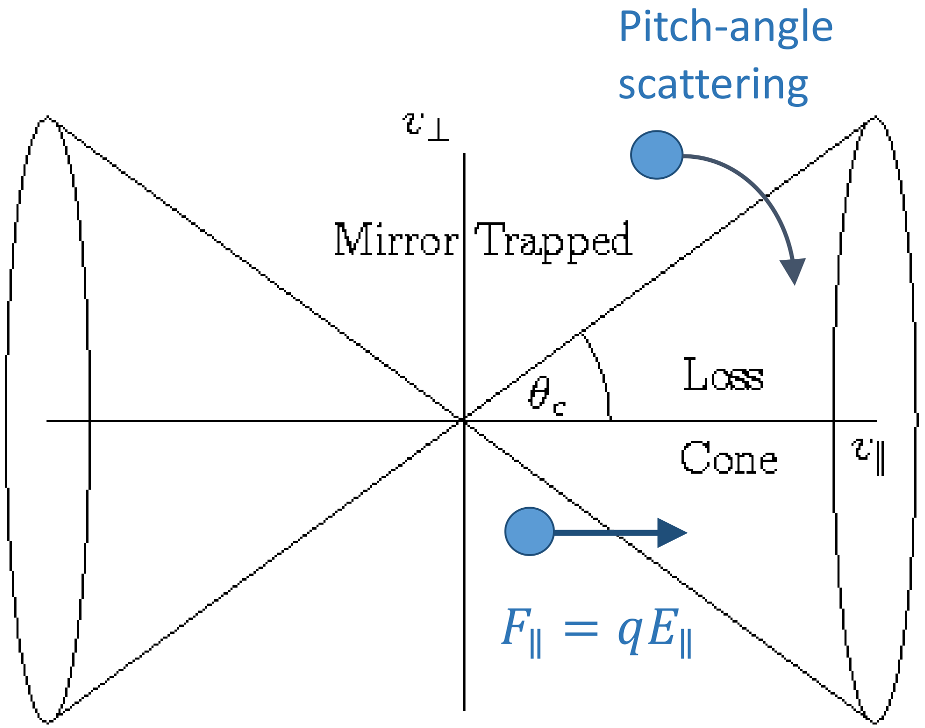
Major classes of auroral acceleration mechanism

a) Quasi-static potential drop (**discrete**)

b) Broadband/Dispersive Alfven wave (**discrete**)

c) Pitch-angle scattering (**diffuse**)

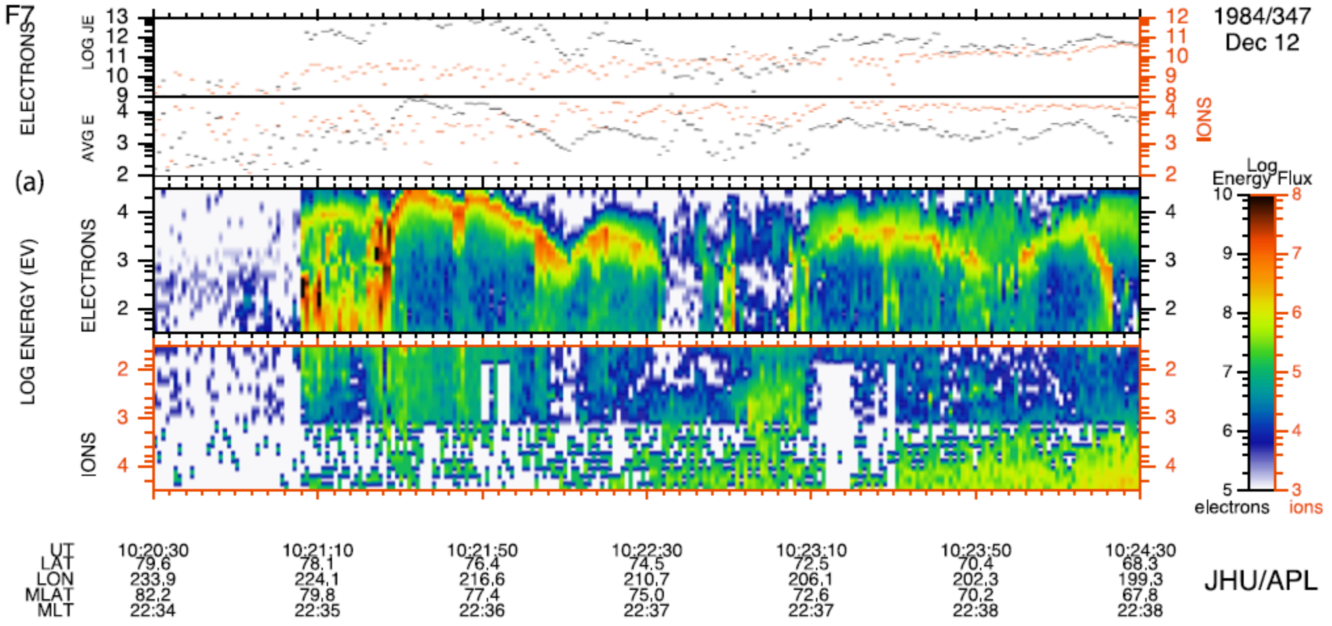
- Not traditional **acceleration** (increase in energy)
- Can precipitate electrons by knocking them into the loss cone with no change of energy



1. Quasi-static potential drop

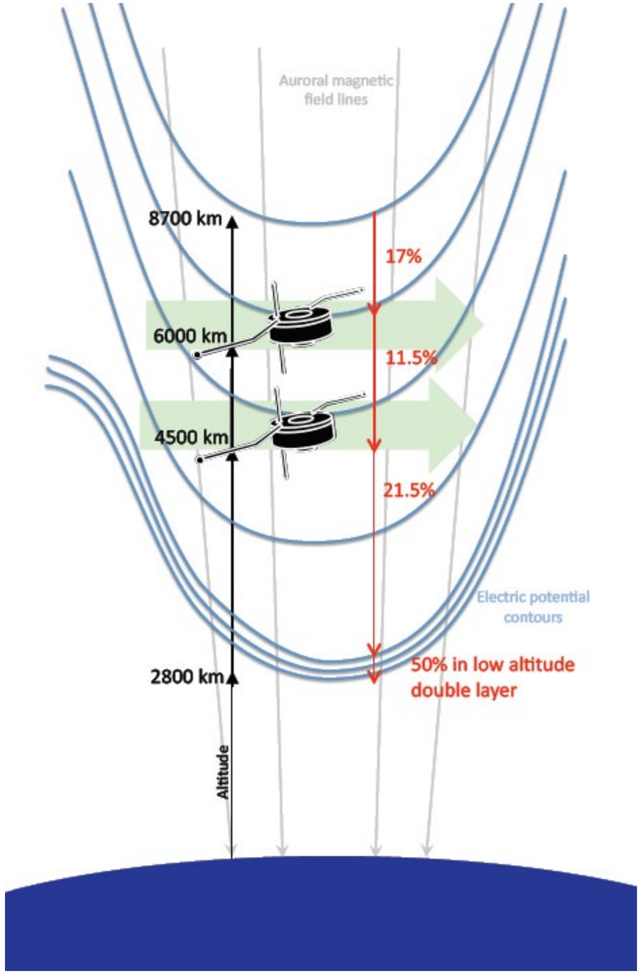
- Inferred from behaviour of electrons seen on low-altitude platforms
- Electrostatic potential difference that is greatest in direction along the field line
- Long-lived compared to electron bounce period, but **not truly static**
- "Inverted-V" structure
  - Narrow-band in DEF

Observations of differential energy flux (DEF) from DMSP



Newell et al., JGR [2009]

Cluster observations



Forsyth et al., JGR [2012]

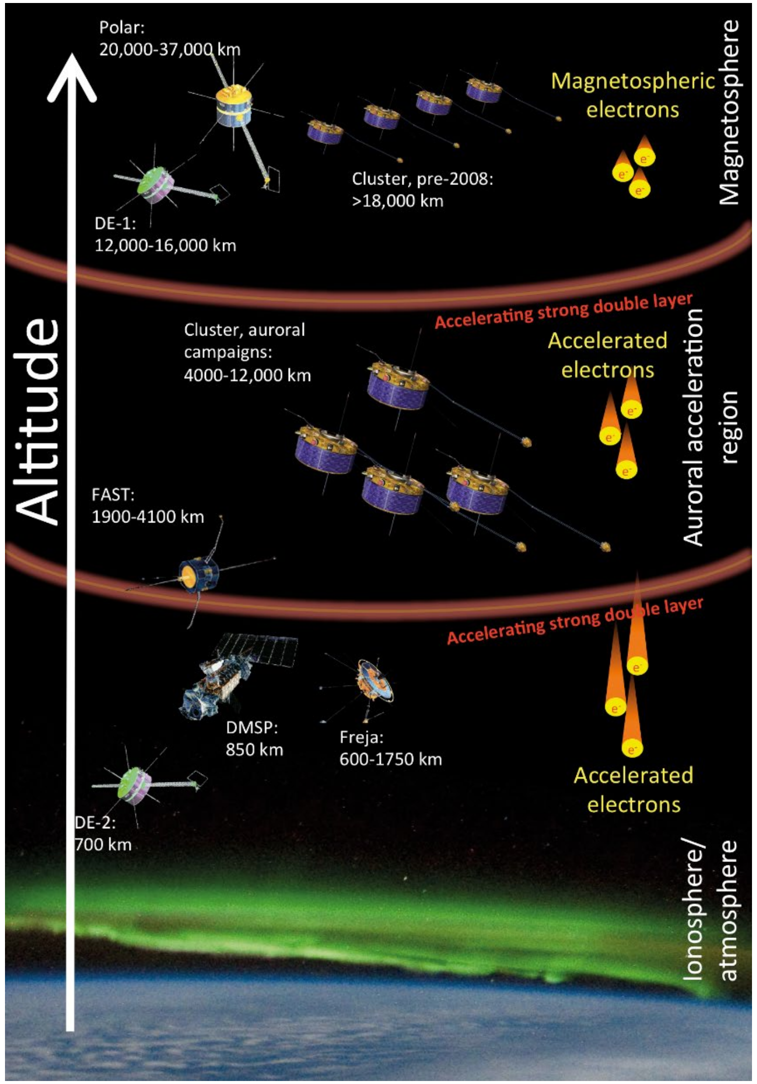
Inverted-V electrons

- Shape caused by spacecraft motion through U-shaped potential structure
- Gradients along field can be both sharp and weak
- Sharp parallel gradients (large $E_{||}$) can
  - Exist as double layers (e.g. *Ergun et al., JGR [2004]; Main et al., GRL [2013]*)
  - Move and change strength (e.g. modelling: *Gunnell et al., AG [2015]*; observation: *Forsyth et al., JGR [2012]*)

Auroral acceleration region

- Bounded by two strong double layers
- Between ~1000km altitude to ~20,000km altitude
- Likely to be much more complicated than picture suggests – **temporal variation**

- Multi-point measurements essential!

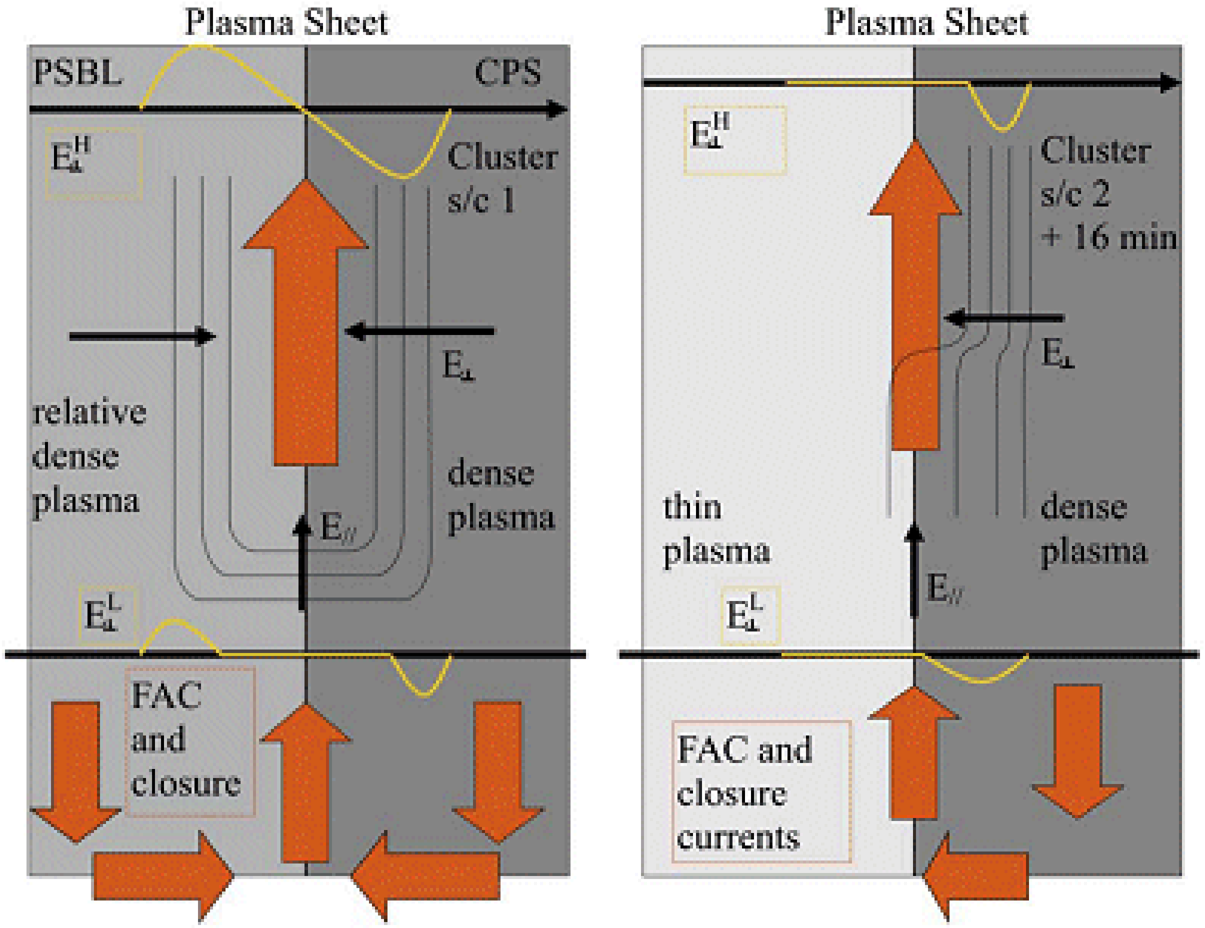


Forsyth et al., Astronomy and Geophysics [2011]

Spatial structure and evolution of potential structures

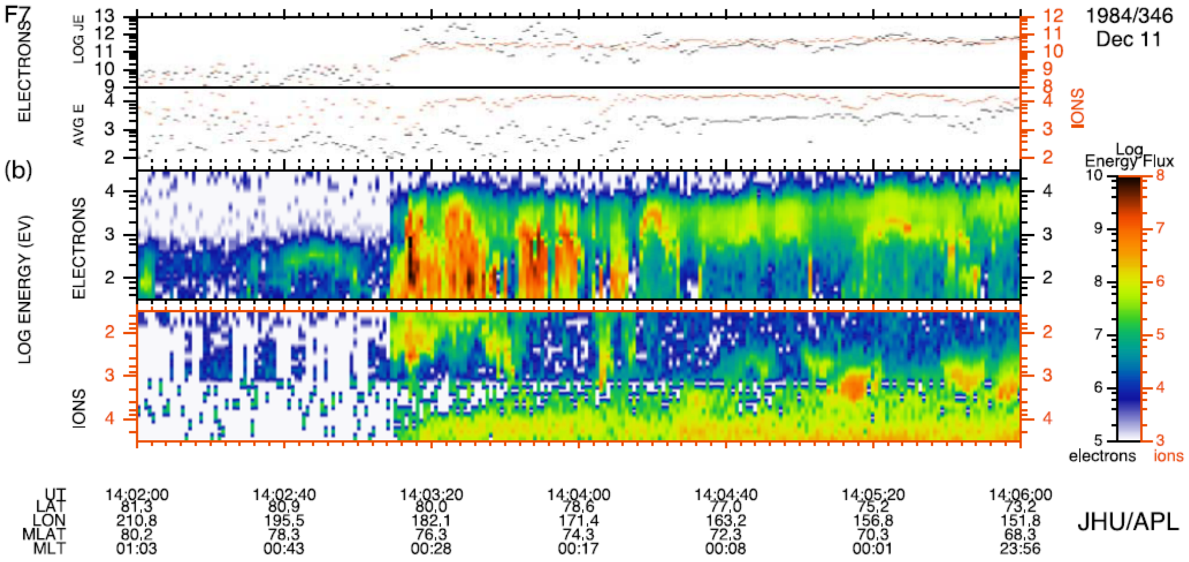
Marklund et al., JGR [2007]

- Can identify existence of U-shaped potential structure from converging $E_{\perp}$
- [Left] Cluster 1 observation suggesting U-shaped potential
  - notice important density gradient between plasma sheet boundary layer and central plasma sheet
- [Right] Cluster 2 observation 16 minutes later suggesting S-shaped potential
  - density depletion in plasma sheet boundary layer



2. Broadband/Shear Alfven wave acceleration

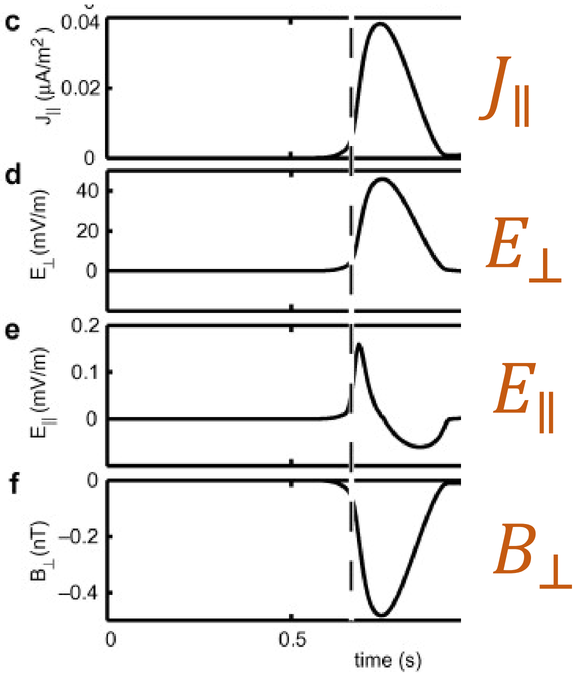
- In DEF, acceleration occurs over a wide range of energies
- Signatures associated with Alfven wave measurements:
  - Low altitude - *Andersson et al., AG [2002]; Chaston et al., GRL [2002]; Paschmann et al., SSR [2002]; Watt et al., GRL [2006]*
  - High altitude – *Wygant et al., JGR [2000,2002]*



Newell et al., JGR [2009]

How do shear Alfven waves support $E_{\parallel}$?

- Shear Alfven waves (SAW) are non-compressional and in MHD limit propagate along the magnetic field
- If you introduce a $k_{\perp}$, waves must support a parallel current
- $\rightarrow$ $E_{\parallel}$ are required



Kinetic simulation results for SAW with $k_{\perp}\lambda_{De}\frac{v_{th,e}}{v_A}\sim 0.4$
Gaussian $E_{\perp}$ introduced into domain
$E_{\parallel}$ develops to support $J_{\parallel}$
Watt and Rankin, ASR [2007]

Incompressible continuity equation implies:

$$\nabla . \mathbf{J} = 0$$

$$k_{\perp}J_{\perp} + k_{\parallel}J_{\parallel} = 0$$

$$J_{\parallel} = -(k_{\perp}/k_{\parallel})\, J_{\perp}$$

Parallel electric field

$v_{th,e} \ll v_A$

$v_{th,e} \sim v_A$

$v_{th,e} \gg v_A$

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

Inertial regime
(Low altitude)
Goertz and Boswell, JGR [1979]

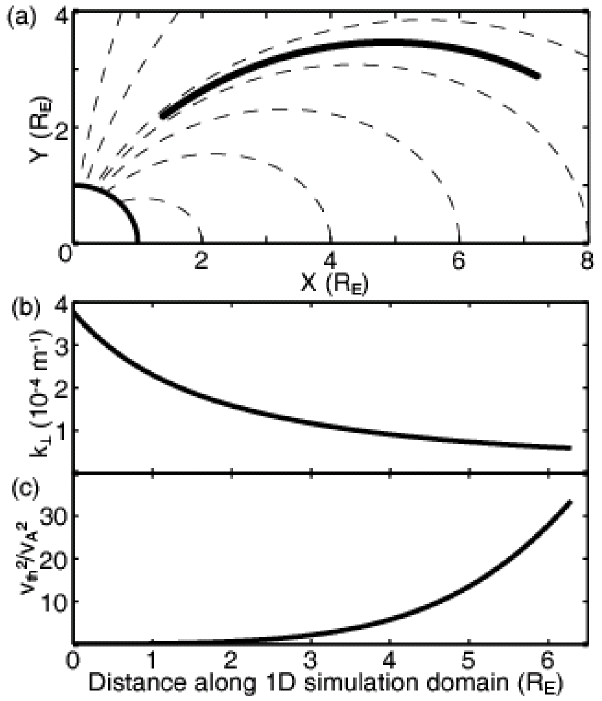
Full complex solution:

Lysak and Lotko, JGR [1996]
Watt and Rankin, PPCF [2008]

$$\frac{E_{\parallel}}{E_{\perp}} = \frac{\lambda_e^2 v_{th,e}^2}{v_A^2} k_{\parallel} k_{\perp}$$

Kinetic regime
(High altitude)
Hasegawa, JGR [1976]

Along auroral field lines, we move from kinetic regime to inertial



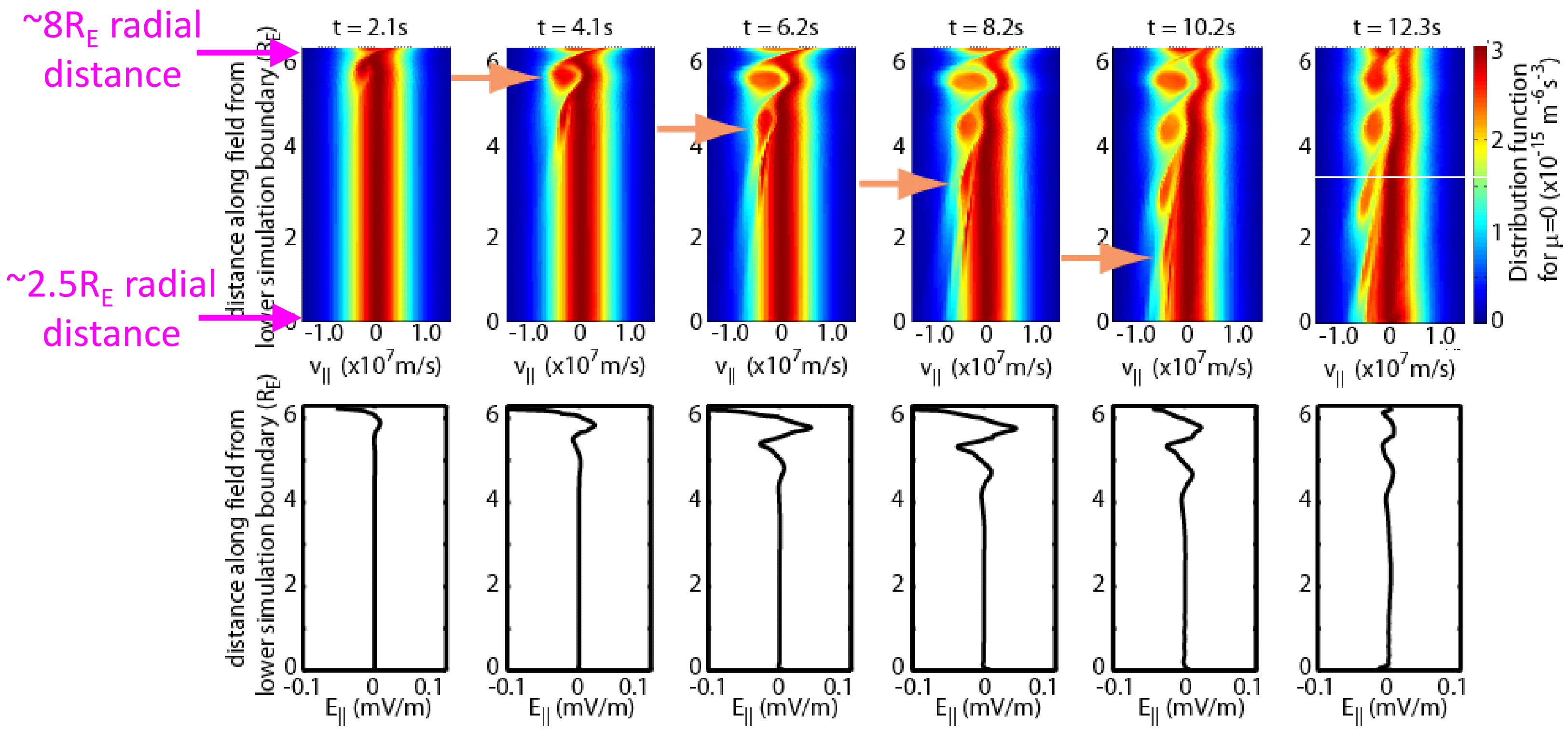
Watt and Rankin, PRL [2009]

- Where does shear Alfven wave "develop" small perpendicular scales/$E_\parallel$?

- In plasma sheet boundary layer due to density gradients (e.g. *Wygant et al., JGR [2002]*)
- As part of turbulent cascade (e.g. *Chaston et al., PRL [2008]*)
- In traditional auroral acceleration region due to density cavity (e.g. *Genot et al., AG [2004]*)

Motion through regimes changes acceleration

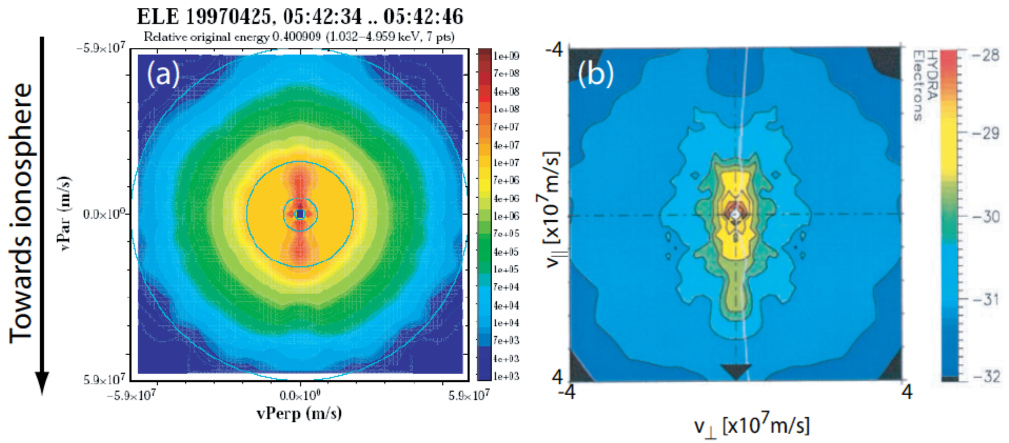
- At high altitude – nonlinear trapping in wave $E_{\parallel}$
  - e.g. *Watt and Rankin [2009]; Artemyev et al., [2015]*
- At lower altitude, $E_{\parallel}$ diminishes and electrons free to stream down field line and precipitate



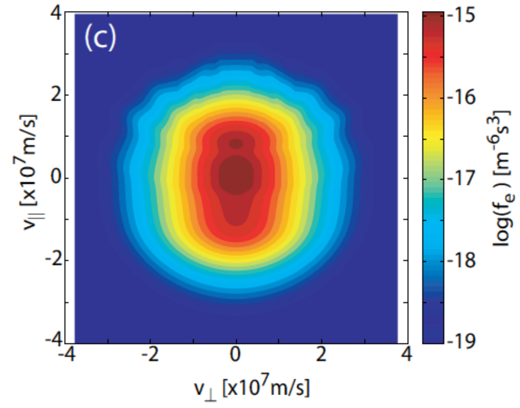
Watt and Rankin, PRL [2009]

If short ⊥ scales develop at high altitude

- Elongation of electron distribution in both upwards and downwards parallel direction seen at low energies **only**
- Towards ionosphere – trapping in wave
- Away from ionosphere – compensation to carry $J_{\parallel}$ needed by wave

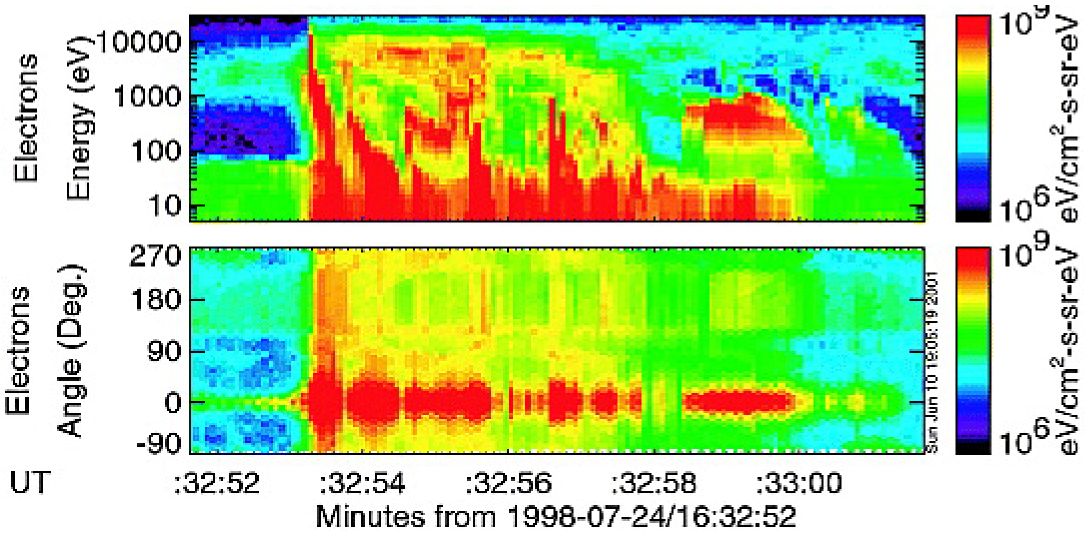


(a) Polar observations, *Janhunen et al., AG [2004]*
(b) Polar observations, *Wygant et al., JGR [2002]*
(c) Kinetic simulation, *Watt et al., Geophys Mono [2012]*

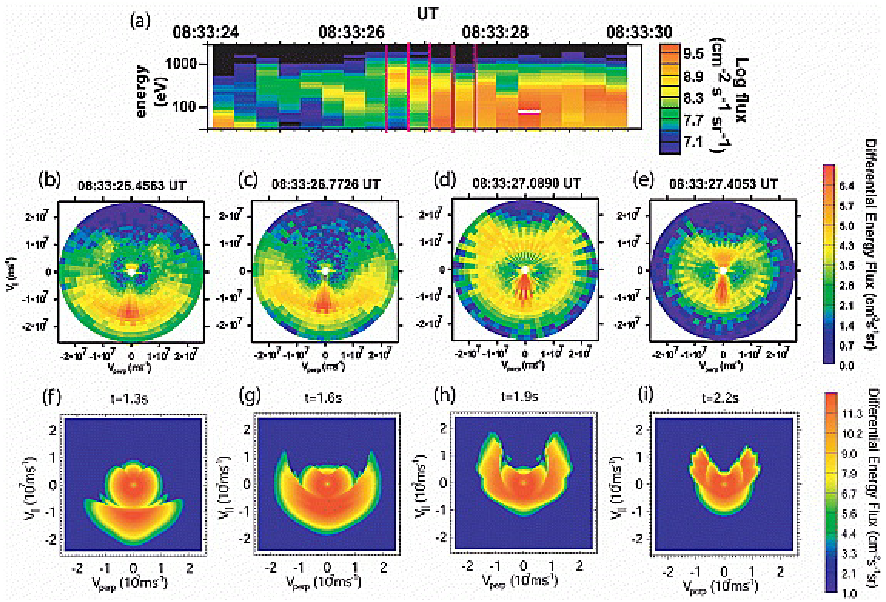


If short ⊥ scales develop at low altitude

Energy-dispersed features commonly seen (e.g. *Andersson et al., AG [2002]*)



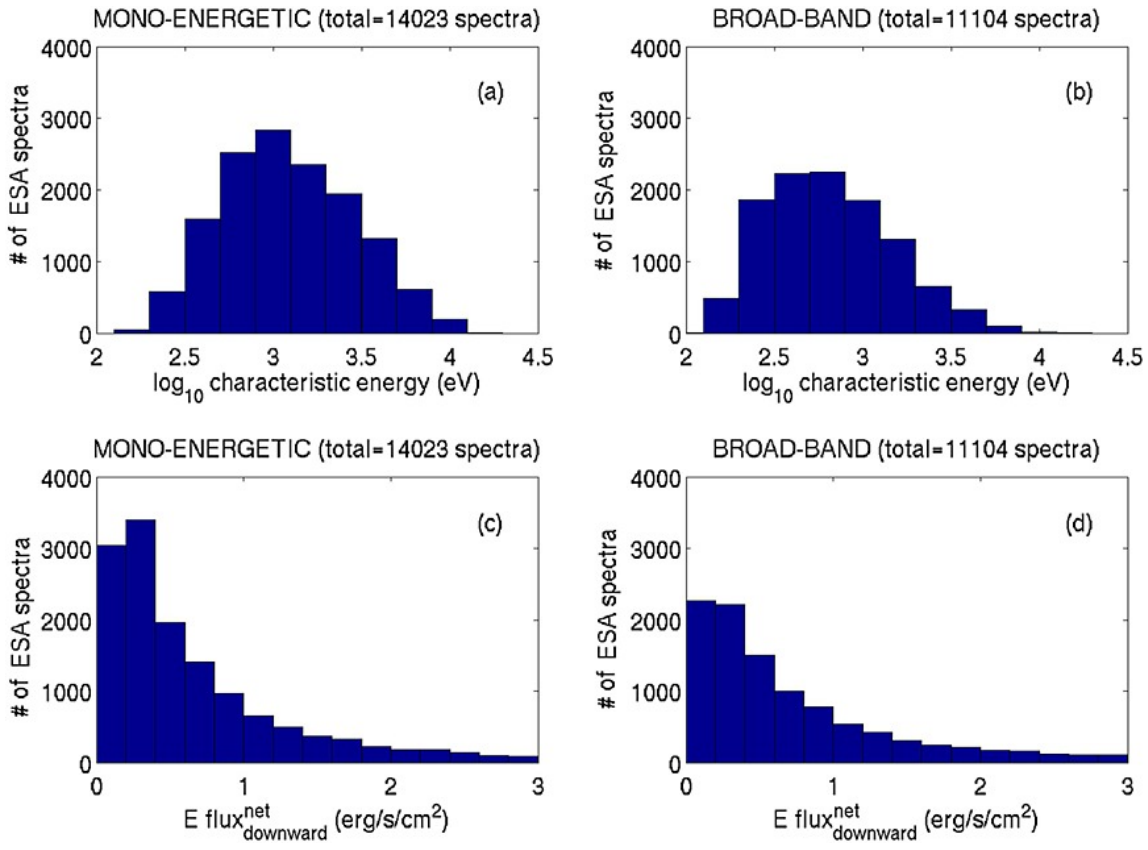
Chaston et al., JGR [2002]



Watt et al., GRL [2006]

Occurrence of types of discrete auroral acceleration mechanism

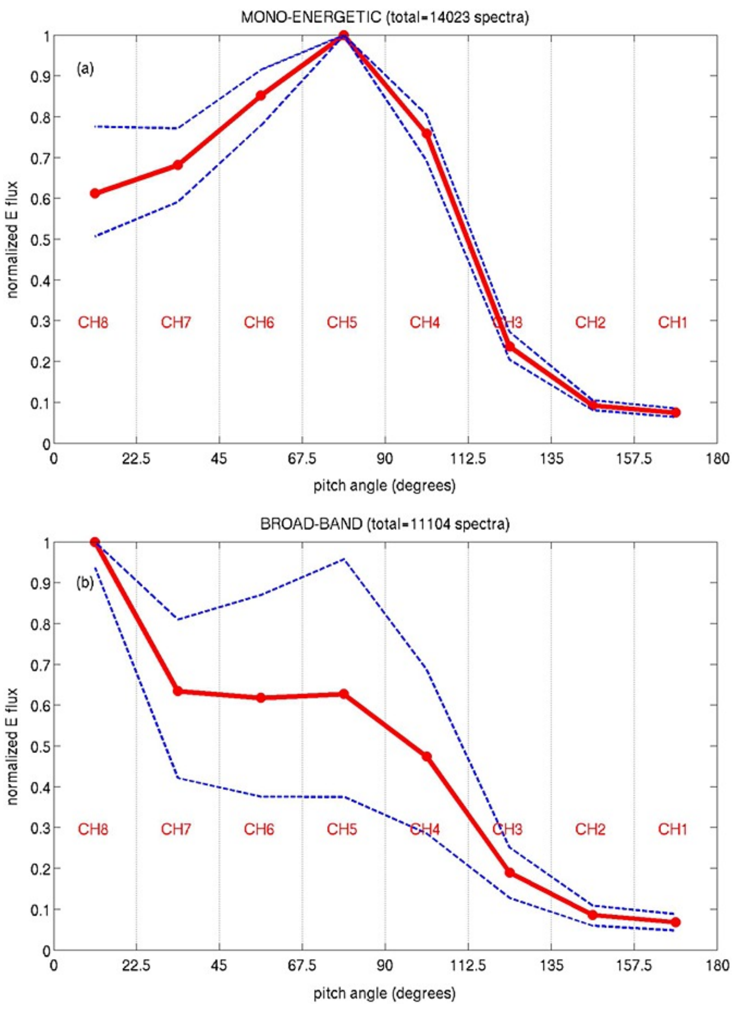
- ~10 months of Science and Technology Satellite-I measurements
- 680km altitude
- $E_{mono} > E_{BB}$
- Total net flux greater for mono than BB
- *Newell et al., JGR [2009]*



Park et al., JGR [2014]

Pitch-angle behaviour of discrete auroral acceleration mechanisms

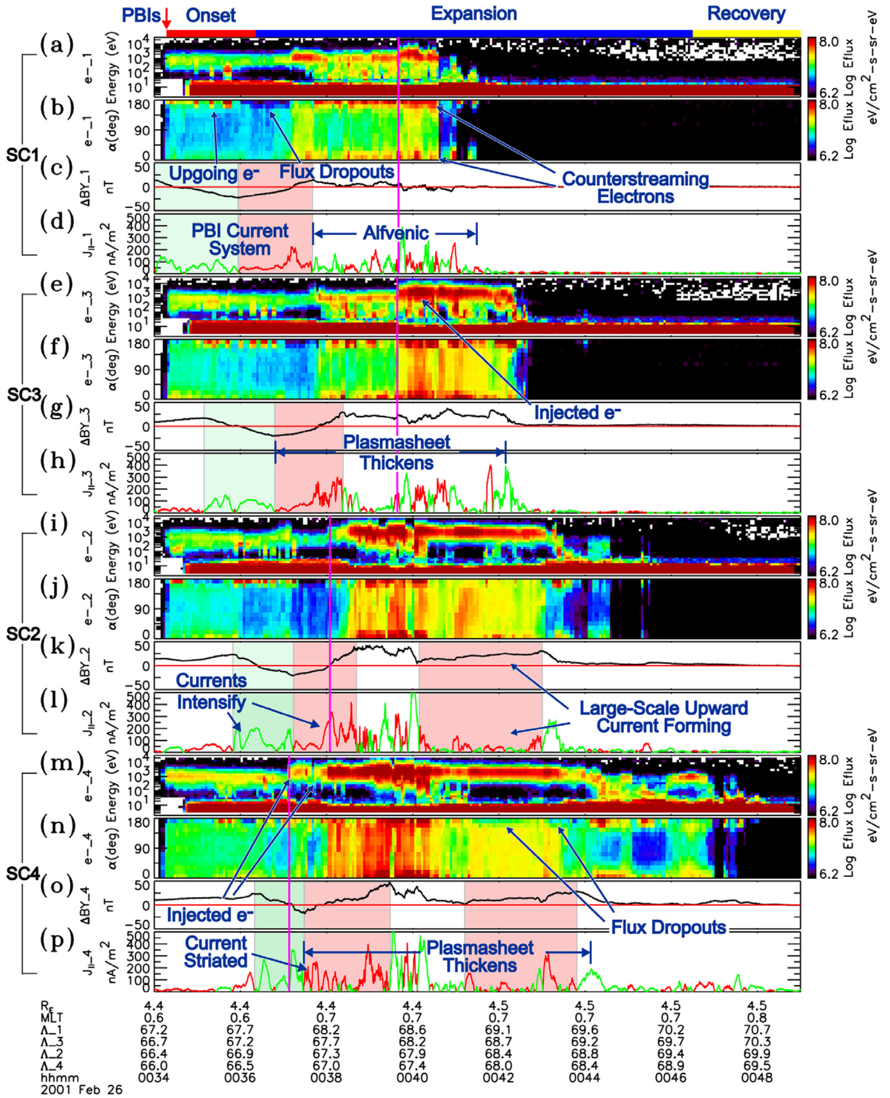
- Monoenergetic acceleration **always** broad in pitch-angle
  - **Always** peaks in channel $67.5° < \alpha < 90°$
- Broadband acceleration **sometimes** broad in pitch-angle
  - But **always** peaks at $\alpha = 0°$



Park et al., JGR [2014]

Relationship between types of discrete acceleration mechanism

- Strength of multi-spacecraft measurements – Cluster
- Temporal and spatial changes
  - *Hull et al., JGR [2010]*
- Temporal and spatial changes near substorm onset
  - *Hull et al., JGR [2016]*



Hull et al., JGR [2016]

4. Auroral Acceleration near substorm onset

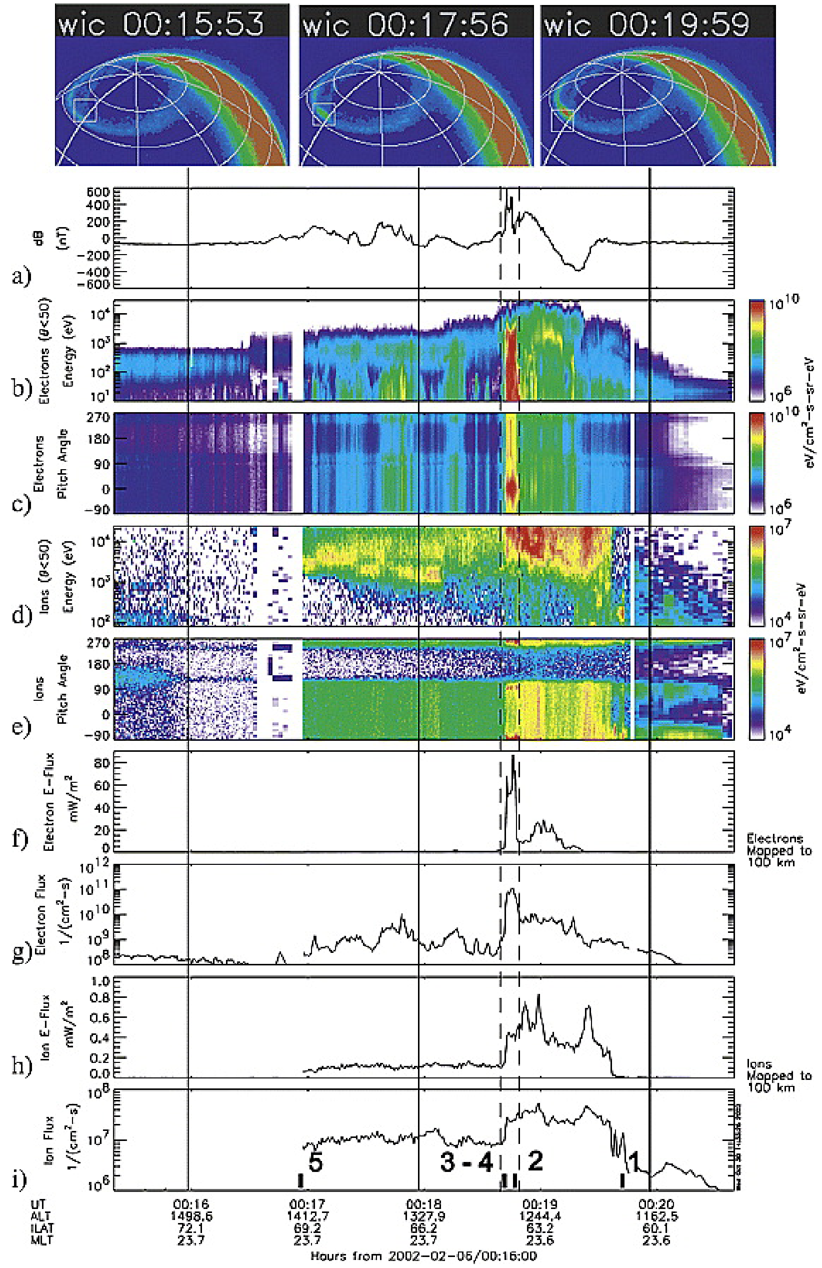
- Evidence for ULF/SAW involvement in substorm aurora
  - from space
  - from the ground
  - from aurora itself

Substorm aurora from space

- FAST spacecraft observations
- IMAGE/UV observations

- Brief passage through region above aurora
- Broadband features coincide with location of onset arc

- See also *Hull et al., JGR [2016]*



Mende et al., JGR, [2003]

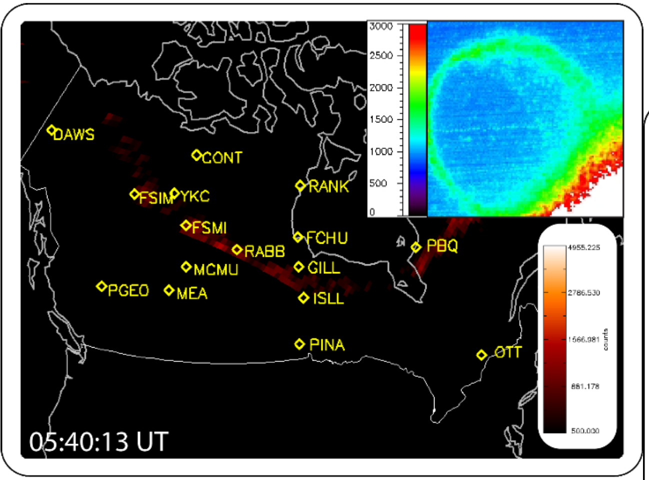
Why would SAW be involved with substorms?

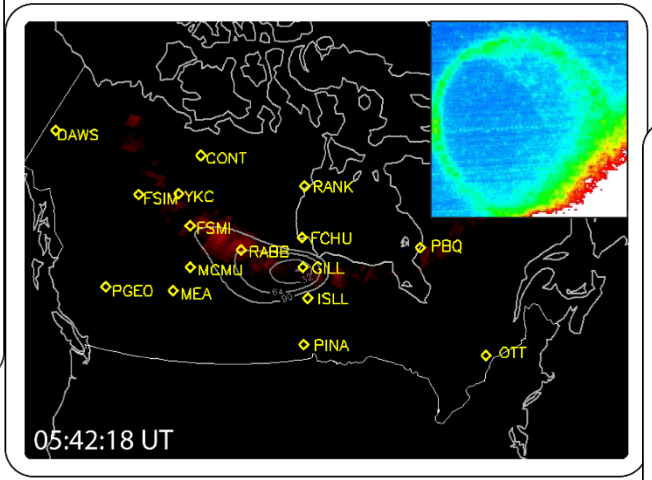
- Long association between ULF waves and substorms
  - see e.g. review by *Olson, JGR, [1999]*
  - Pi2 (40-150s band e.g. *Kepko & Kivelson, 1999*) and Pi1 (1-40s band e.g. *Bösinger and Yahnin, 1987*)

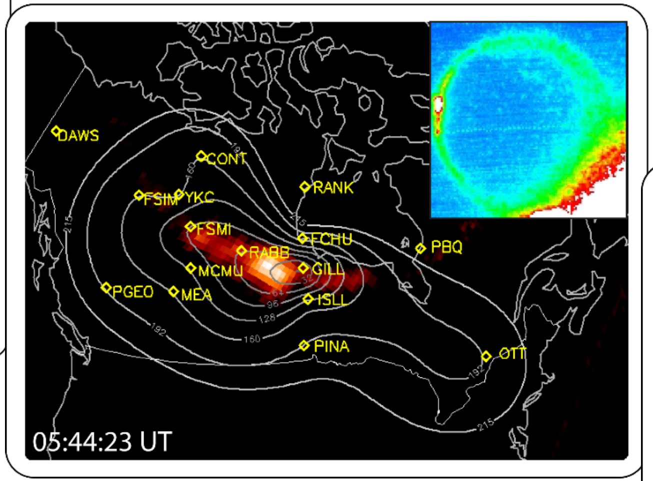
- NB - ULF waves are not necessarily shear Alfven waves (SAW)
  - more evidence in following slides

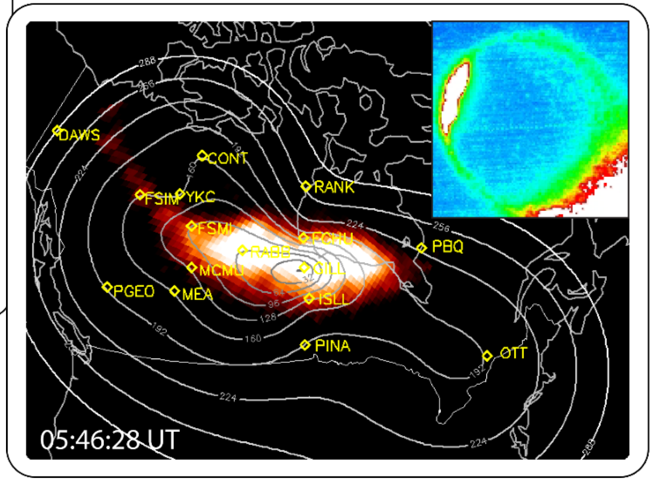
ULF association with substorms

ULF waves occur at same time and place as auroral brightening







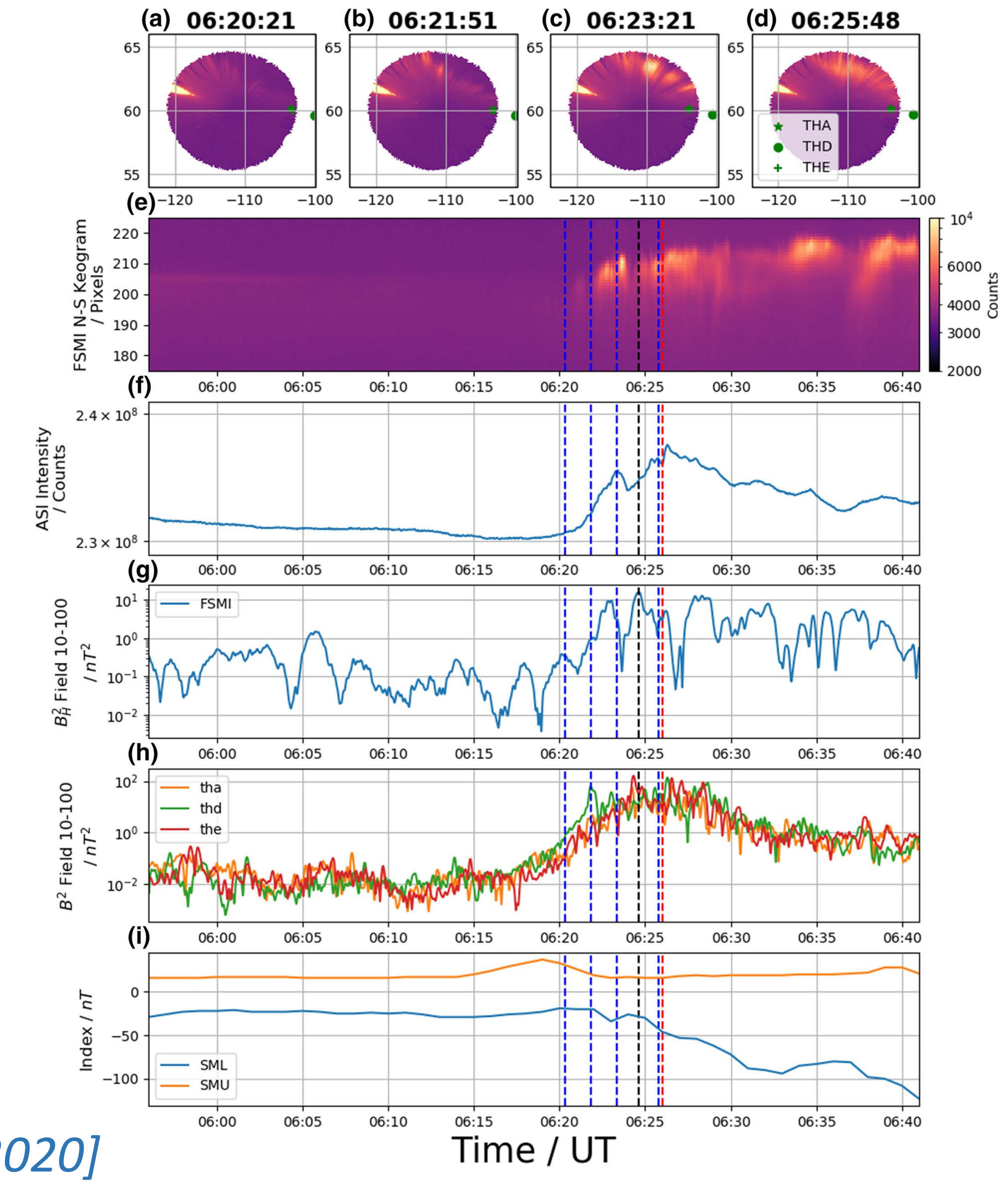


See *Milling et al., JGR [2002]* and *Smith et al., JGR [2020]* for wave technique

Adapted from Murphy et al., JGR, [2009]

ULF wave growth at substorm onset also observed in space

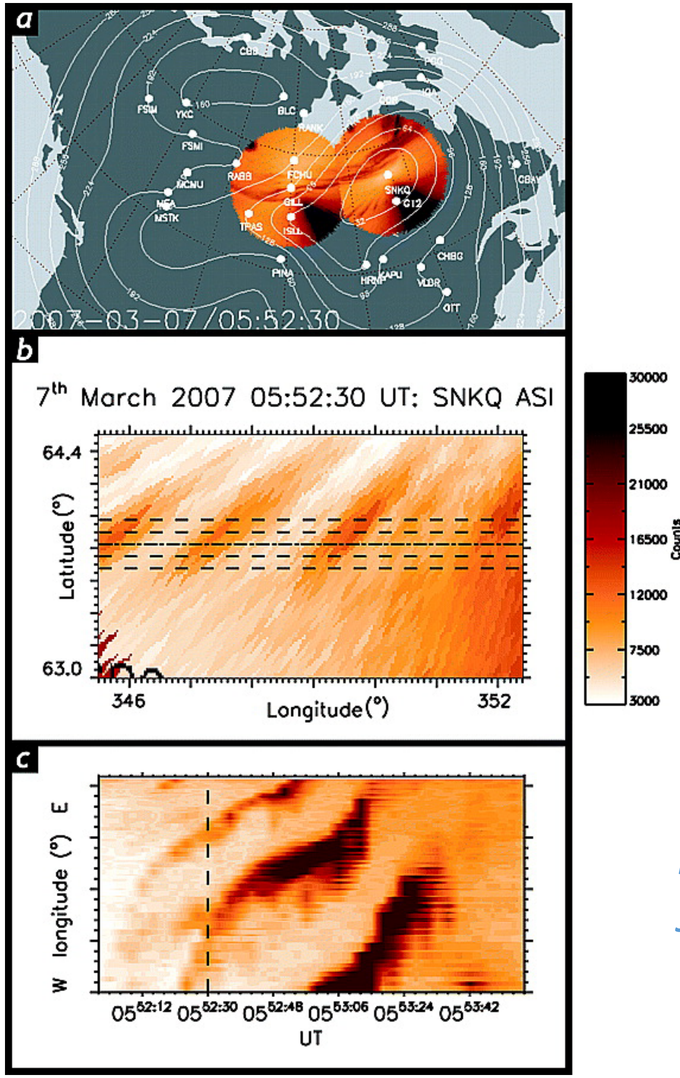
- Exponential brightening of aurora (FSMI ASI)
- Exponential growth of ULF wave power on the ground (CARISMA)
- Exponential growth of ULF wave power in space (THEMIS)
- 175 events with similar growth characteristics
- THEMIS observations focused at pre-midnight, ~10R_E downtail



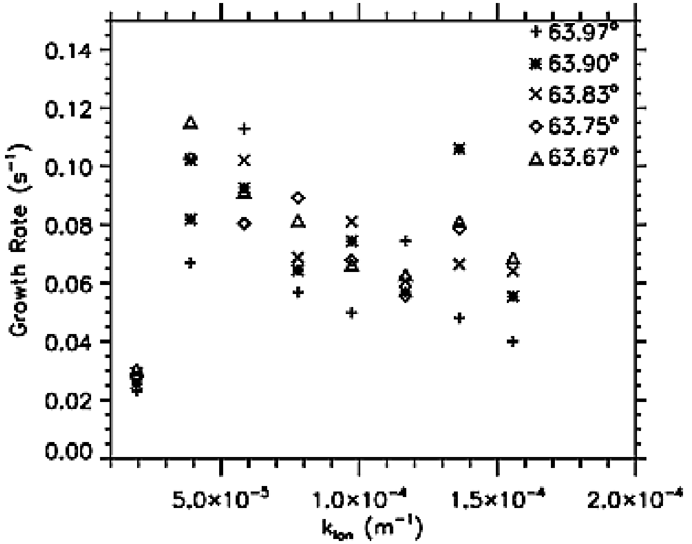
Smith et al., JGR [2020]

Growth of substorm auroral brightness shows wave-like structure

- Azimuthal structure
- Temporal structure
- Brightness associated with each perpendicular wavenumber grows **exponentially**



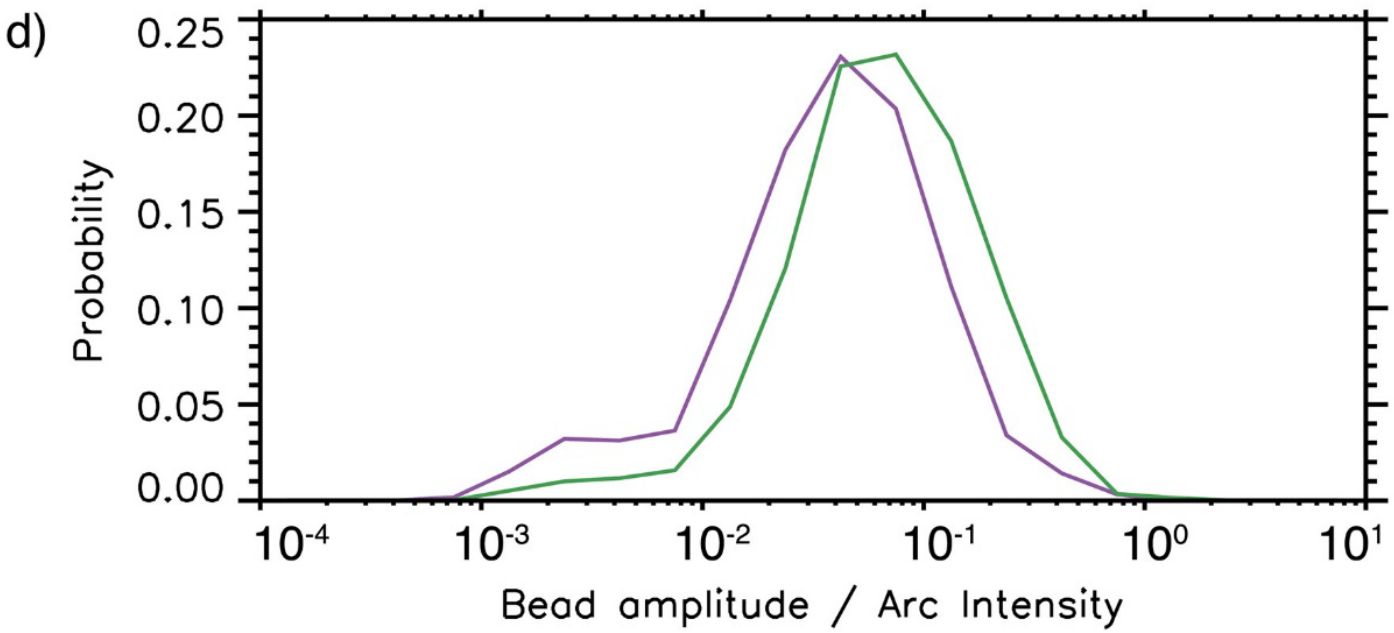
Growth rates for auroral brightness with $k_\perp$



Rae, Watt et al., JGR, [2010]

Beads are typical onset features

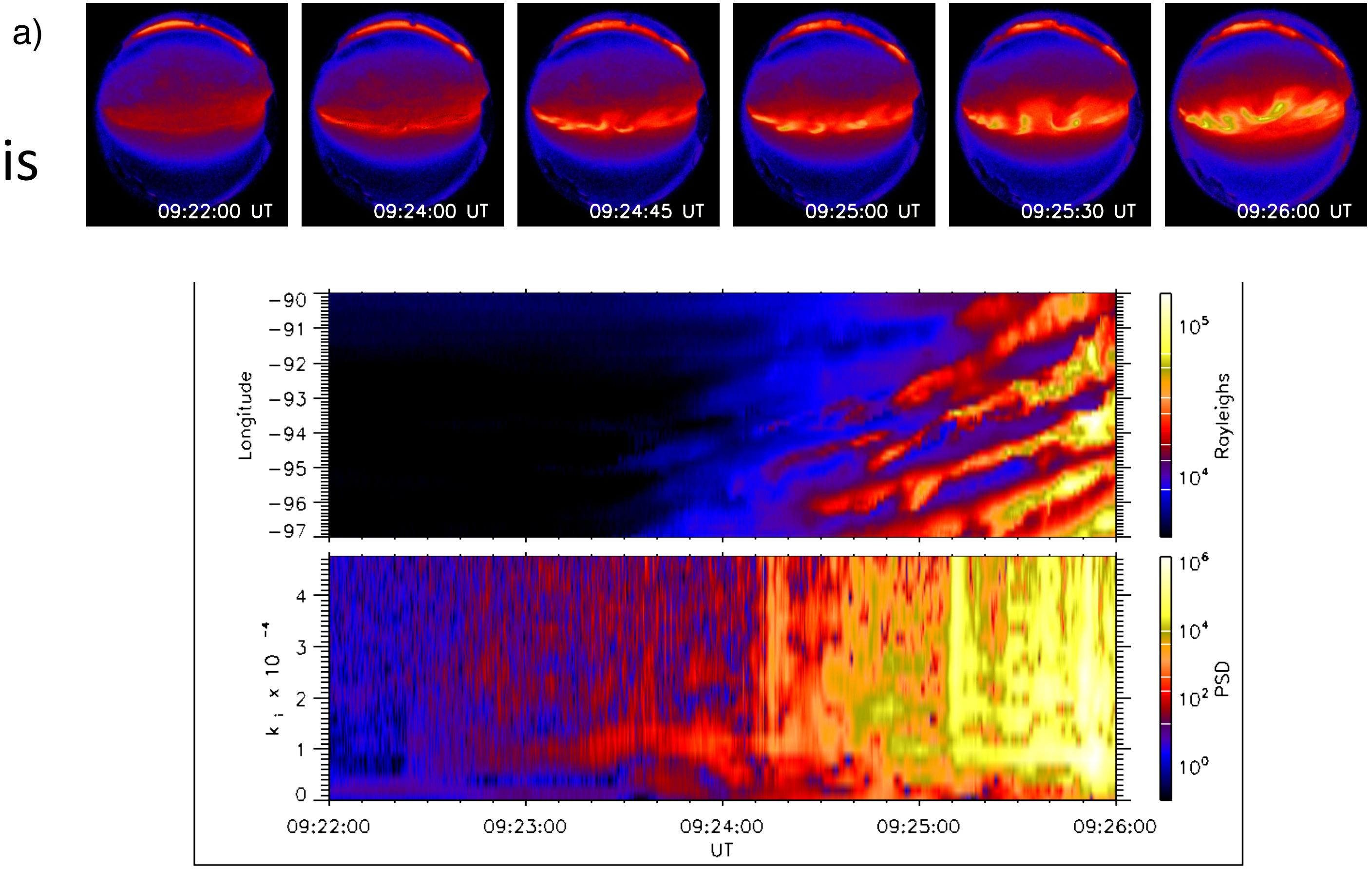
- >90% of onset arcs in isolated substorms with well-identified growth phases display azimuthal structuring



From Figure 3, Kalmoni et al., GRL, [2017]

Using high-cadence auroral images

- We can construct a frequency/wavenumber analysis of the beaded auroral features using Fourier analysis



Kalmoni et al., Nature Comms [2018]

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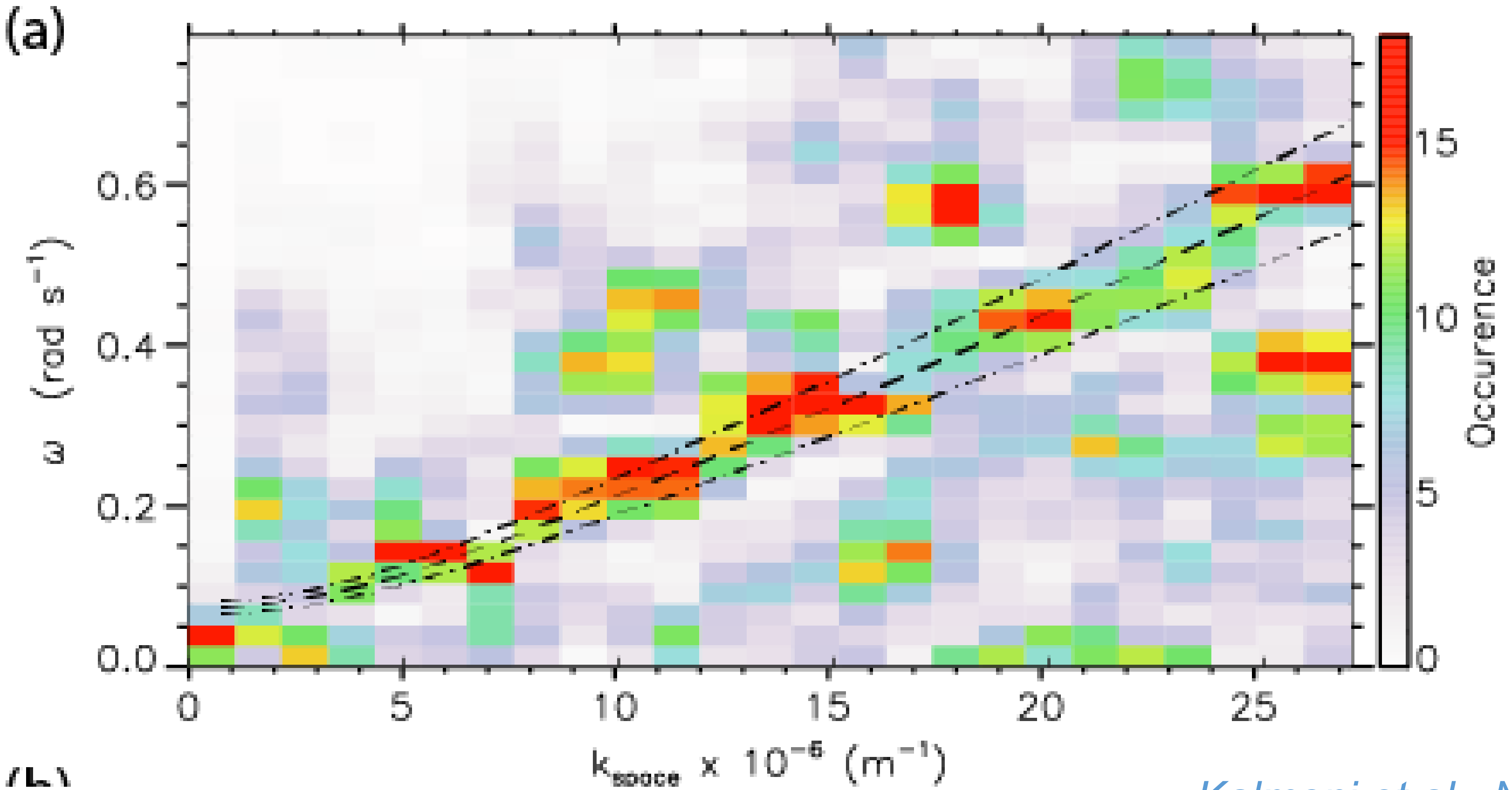
Comparison to the full warm plasma dispersion relation for shear Alfven waves $\lambda_{perp} << \lambda_{parallel}$



Kalmoni et al., Nat. Comms [2018]

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Conclusion – for substorm aurora part!

- Evidence for shear Alfven waves driving substorm **onset** aurora is mounting
  - Broadband acceleration signatures seen in space
  - Beading of onset arc
  - Analysis of temporal and spatial features of aurora
  - Wave growth in space

- Why are ULF waves growing exponentially pre-midnight, ~10R_E downtail at substorm onset?
- Are the growing waves SAW, or are they other waves coupling to SAW?

Future thoughts – many remaining unanswered questions

- What supports auroral arcs?
- Why are they thin in north-south direction?
- What's the relationship between SAW-driven aurora and monoenergetic aurora?
- What controls the shape of patchy aurora?
- How is the exponential growth of ULF waves associated with substorm onset?

Multi-point observations along and across field – electric field is as important as electron measurements!

Kinetic modelling of magnetosphere-ionosphere coupling