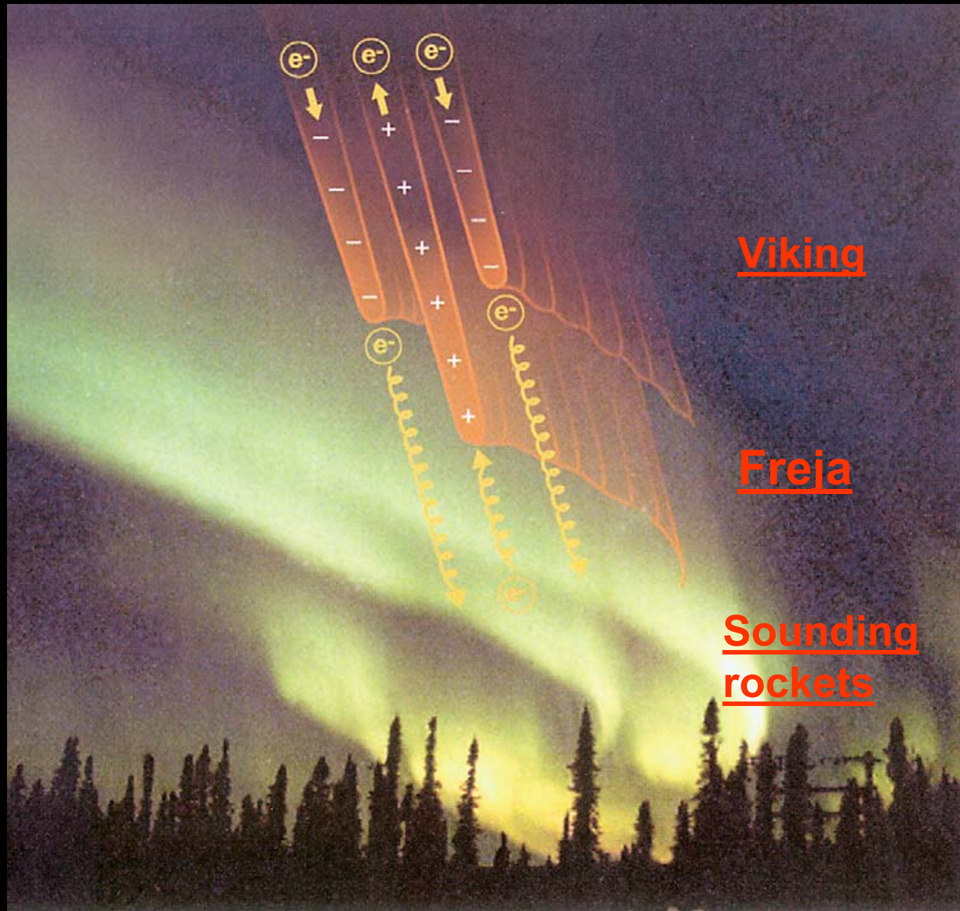
Auroral Electric Fields observed by sounding rockets & satellites below, within, & above the acceleration regions

Cluster



Viking

Freja

Sounding rockets

G. T. Marklund

Space & Plasma Physics
EES, KTH, Stockholm

STIMM-2, Sinaia
June 12-16 2007

OUTLINE

1. Low-and Medium Altitude Auroral E-fields & Potentials

- Rocket observations of arc-associated E-field
- Freja results on the aurora & return current
- Viking E-field characteristics within / above the acceleration region

2. High-Altitude Auroral E-fields & Potentials: Cluster

- Scale sizes of E-fields, Ne-gradients, and FACs
- Characteristics of U^+ & U^- -potentials
- Location of U & S-potentials wrt PS-boundaries
- Evolution of U^+-potential & N_e- hole
- Widening of downward FAC sheet
- Potential- & FAC change as PSBL thins

3. Ionospheric Coupling of Auroral E- Fields & Potentials

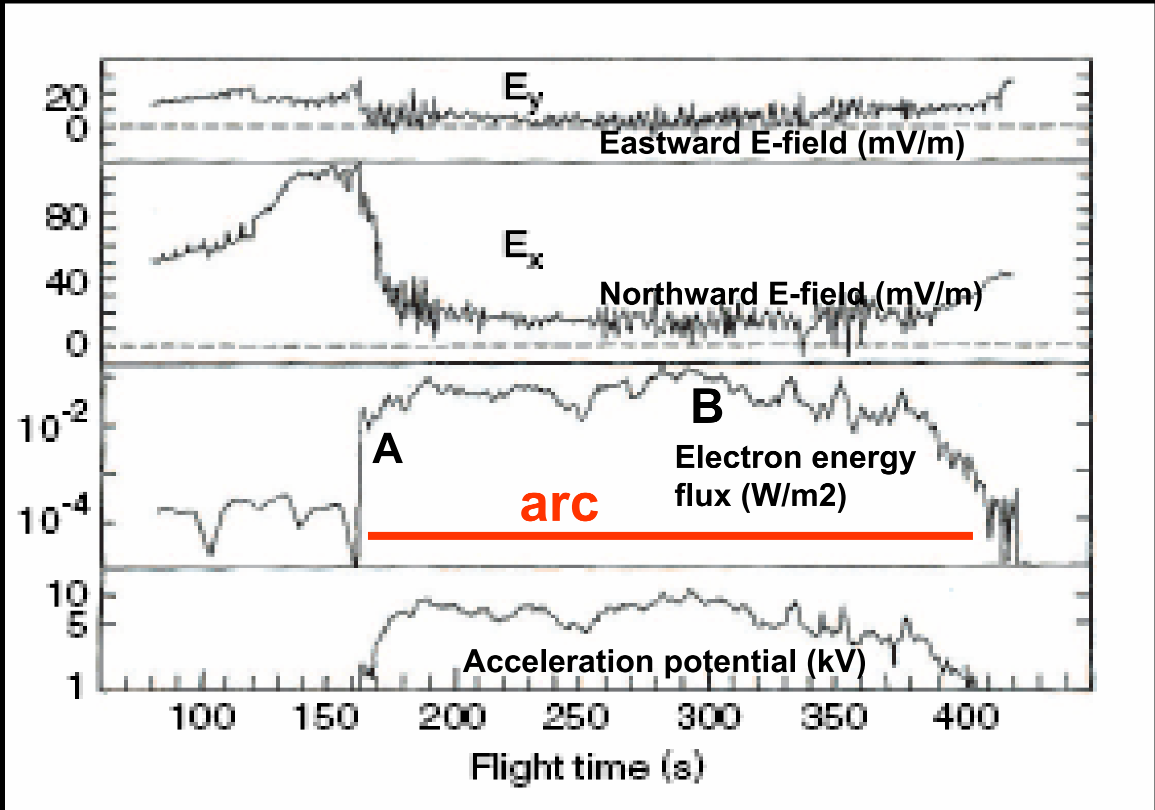
- Approach
- Results from Cluster events
- Correlation $E – j_{||}$ in downward FACs
- FAST results for downward FACs
- DE-1 & 2 comparisons

4. Summary

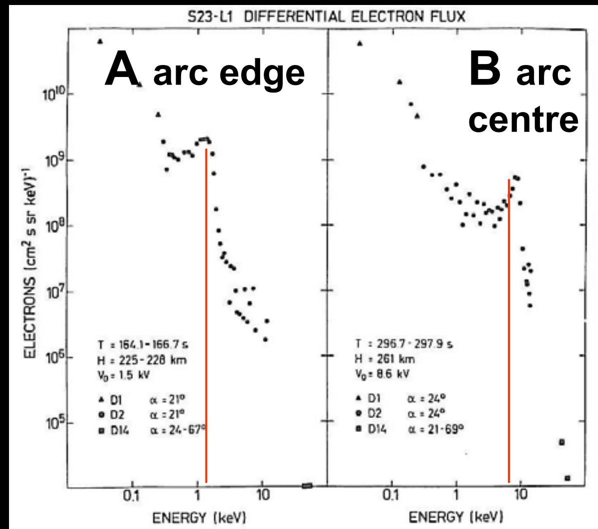
Low-Altitude Auroral E-fields

Rocket observations in the auroral ionosphere

PRE-BREAK-UP ARC



Electron energy spectra



$$E_{arc} = E_{ambient} + E_{pol}$$

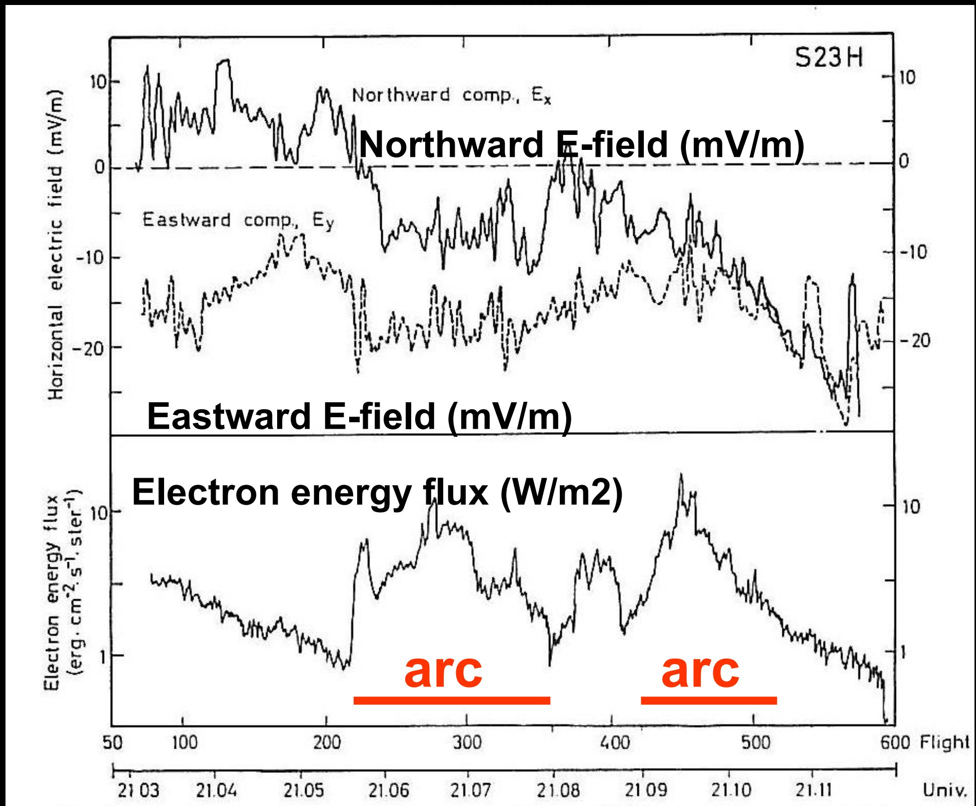
N-ward S-ward

E-field & Joule heating <u>anticorrelated</u> with arc & particle heating

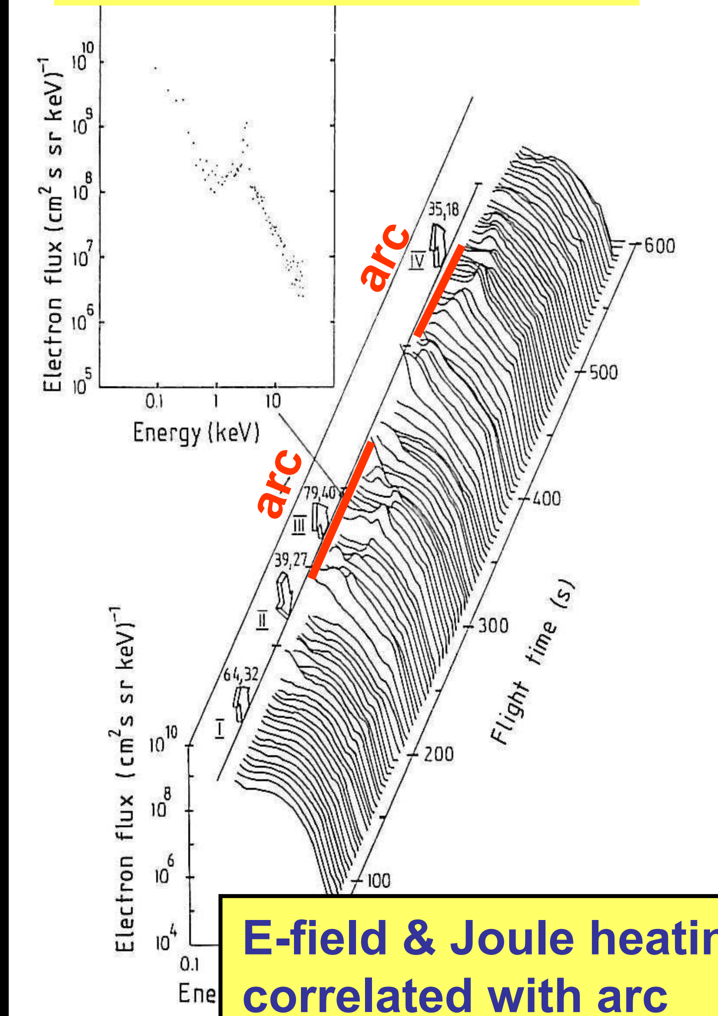
Low-Altitude Auroral E-fields

Rocket observations in the auroral ionosphere

BREAK-UP ARCS



Electron energy spectra



$$E_{arc} = E_{ambient} + E_{pol}$$

NW-ward S-ward

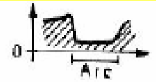
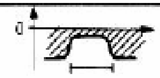
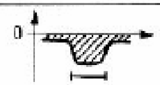
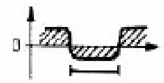
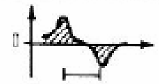
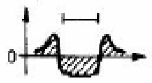
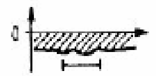
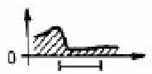
E-field & Joule heating
correlated with arc
& particle heating

Low-Altitude Auroral E-fields Arc classification based on rocket & radar observations

$$E_x^A = E_0 + J_{\parallel} / \Sigma_P^A$$

Pol. arc (E_0) — Birkeland current arc ($J_{\parallel} / \Sigma_P^A$)

$$E_0 = (\Sigma_P^E / \Sigma_P^A)\, E_x^E + (\Sigma_H^A / \Sigma_P^A - \Sigma_H^E / \Sigma_P^A)\, E_y^E$$

Arc category	Subtype	E_x-conf	Ex (amb)	Ey (amb)	E pol	Examples
1. POLARISATION ARCS	I_a: evening-anticorrelation		large, N-ward	small, E- or W-ward	S-ward	Marklund et al. (1982) Cahill et al. (1980) de la Beaujardière et al. (1977)
	I_b: morning-anticorrelation		S-ward	small, E- or W-ward	N-ward	Theile et al. (1981) Ziesolleck et al. (1983) Potter et al. (1970)
	I_c: correlation		S-ward	W-ward	S-ward	de la Beaujardière et al. (1977)
	I_d: double-reversal I		N-ward	W-ward	S-ward	Marklund et al. (1983) Carlson and Kelley (1977)
2. BIRKELAND CURRENT ARCS	II_a: inverted V (single or triple reversal)		small, N- and S-ward	small, typic. W-ward	0	Burch et al. (1976)
	II_b: double-reversal II		small, N-ward	small, E- or W-ward	0	Edwards et al. (1975)
	II_c: non-correlation		S-ward	typ. W-ward	0	Kintner et al. (1974) Mozer and Fahleson (1970)
3.COMB ARCS	III_a: evening asymmetric		large N-ward	small, E- or W-ward	probably S-ward at equatorward arc edge, small at the poleward	Stiles et al. (1980) Evans et al. (1977)

Freja results on the Aurora & Return Current

600 km-1760 km

Inverted-V's of km-scales

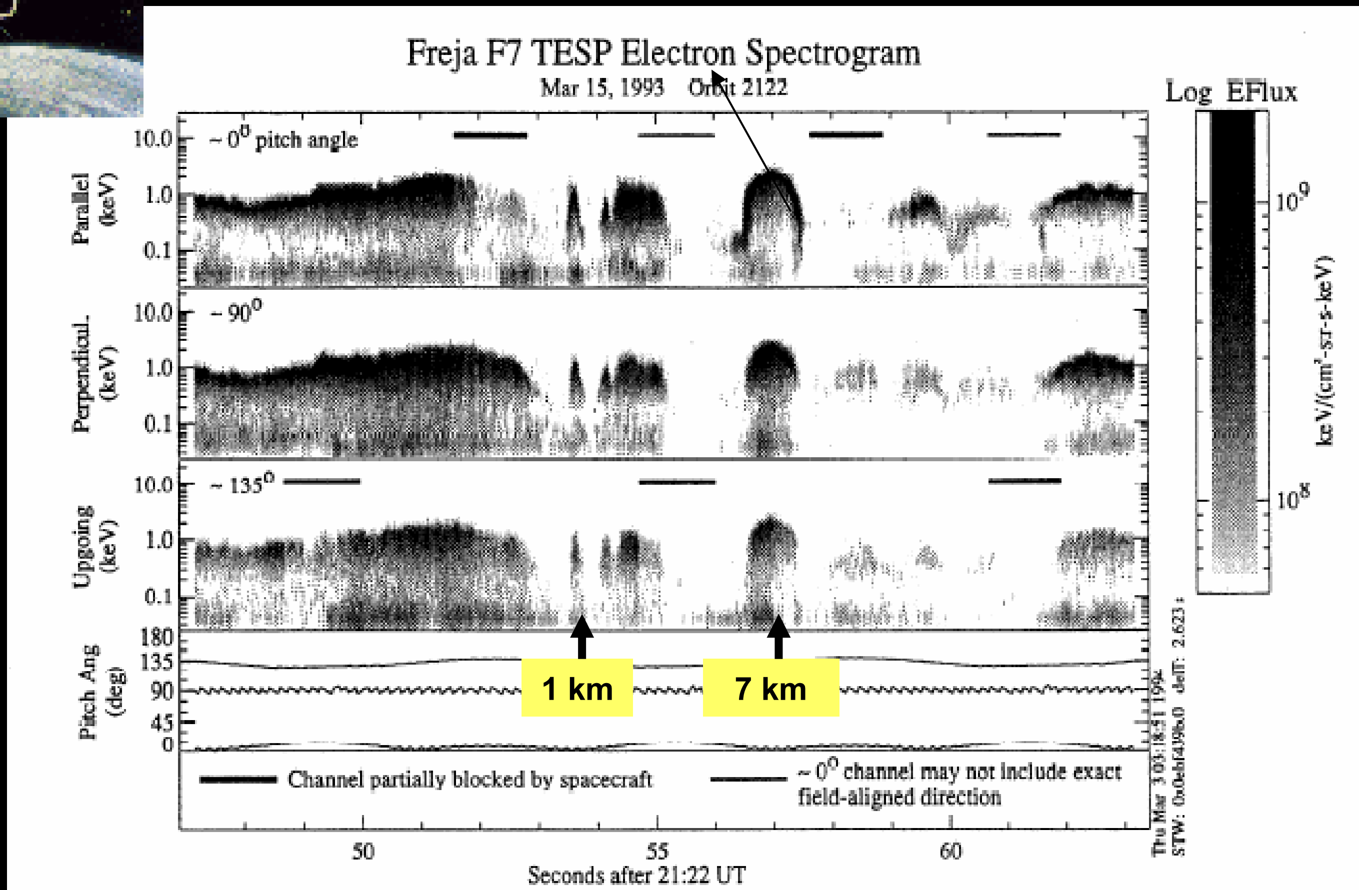
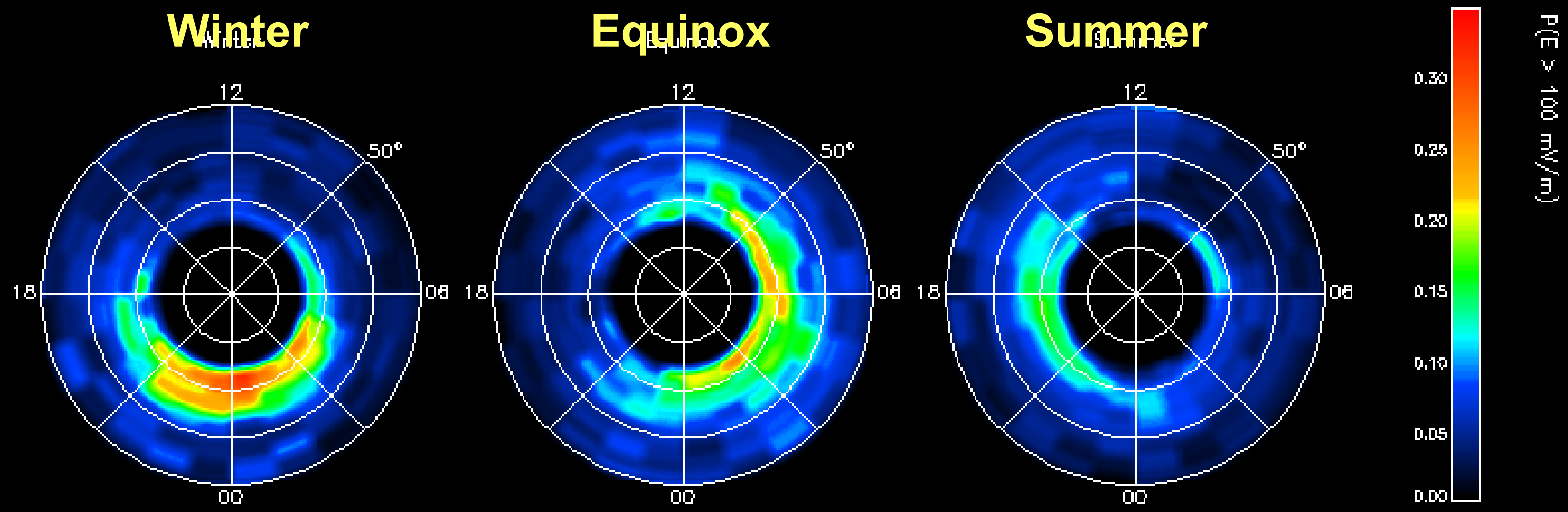


Figure provided by Manfred Boehm

Freja Results on the Aurora & Return Current

600 km-1760 km

Statistical study of intense E-fields



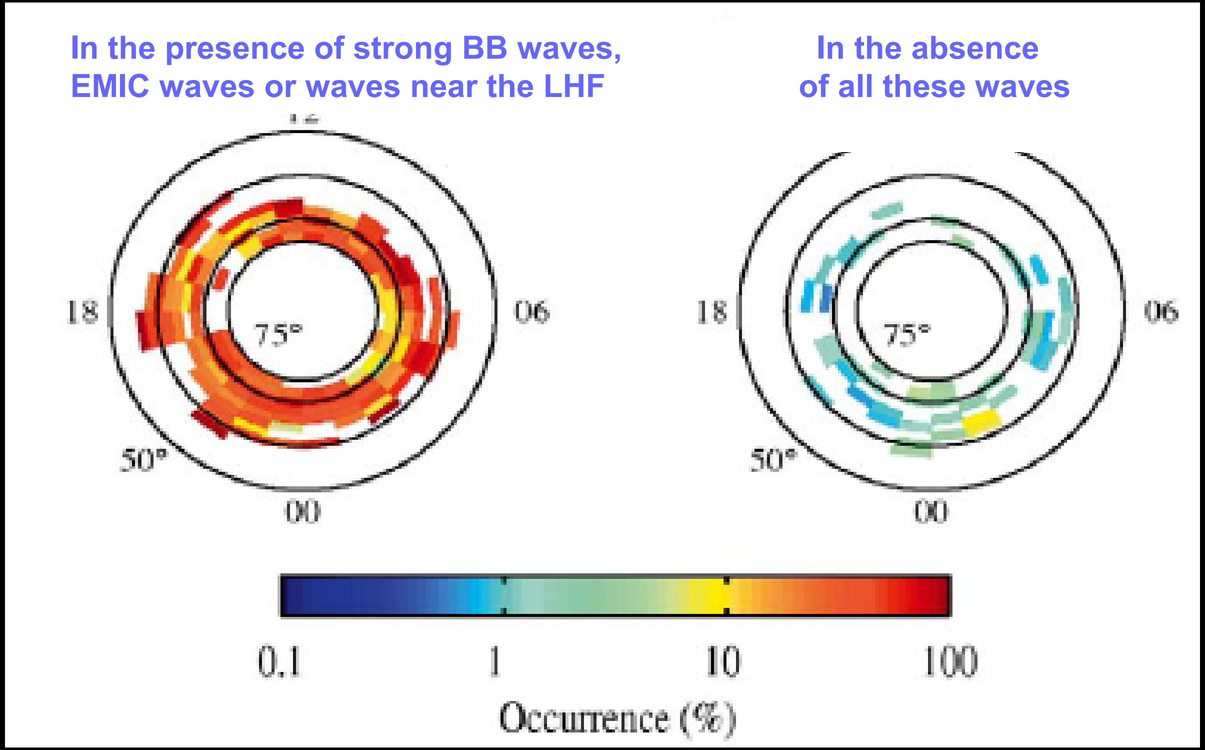
Occurrence rate of E-fields > 100 mV/m

Peak occurrence during winter solstice & 00 MLT

Figure provided by Tomas Karlsson

Freja Results on the Aurora & Return Current

Waves efficient for ion heating

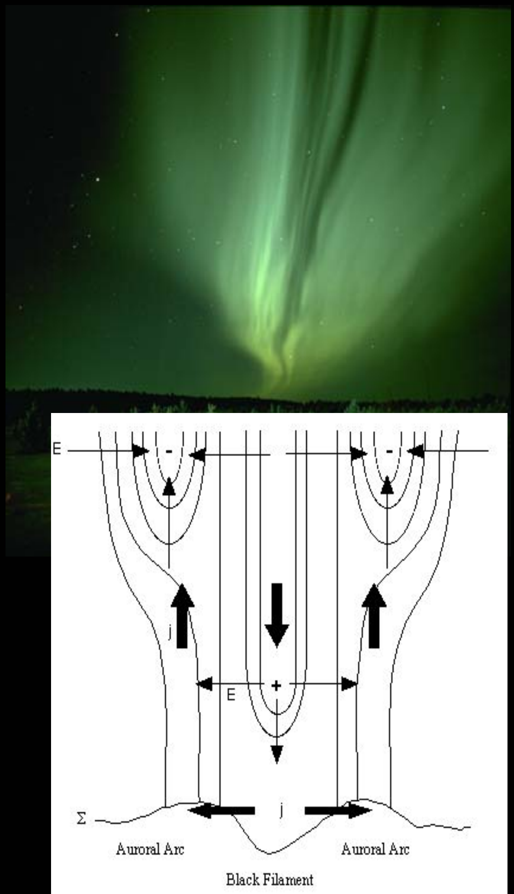


Probabilities of detecting energized O^+ ions in the N-hemisphere

After Hamrin et al., (2002)

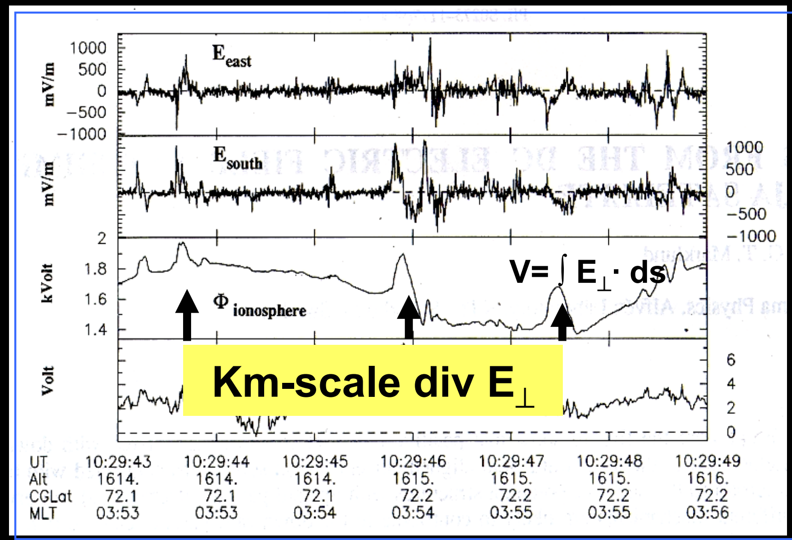
Freja results on the Aurora & Return Current

Return Current Characteristics



Marklund et al, GRL94, AG95, JGR97,

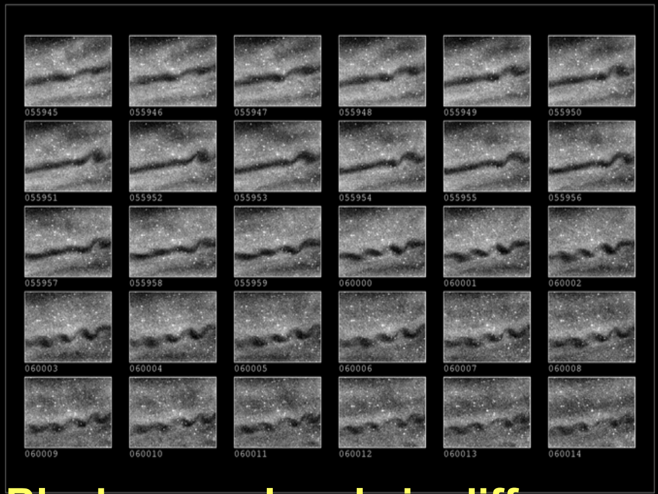
Freja E-field



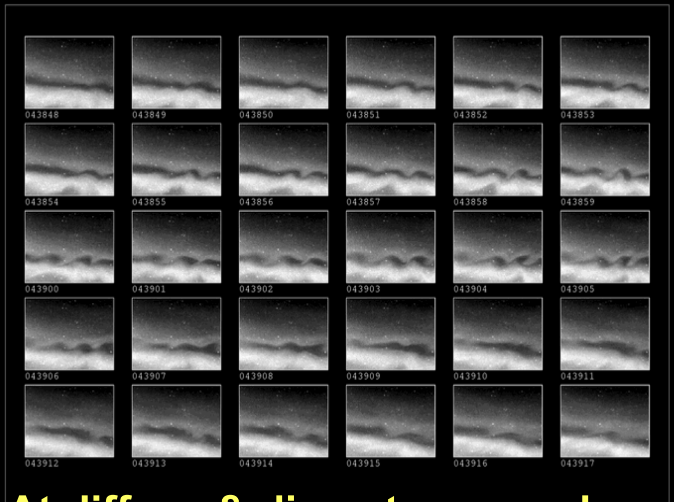
- Quasi-static, diverging electric fields & U^+ /S -potentials
- Up-going accelerated field-aligned electrons
- Fast electron solitary waves, electron holes, DL’s *
- Ion heating $\perp$ B, energetic conics, ”pressure cooker”
- Downward accelerated protons
- Small-scale N_e-cavities and E-region N_e-holes
- Strong wave activity (BBELF, VLF saucer source region)
- Current-voltage relation ?

Return Current Phenomena

Black Aurora, the optical signature



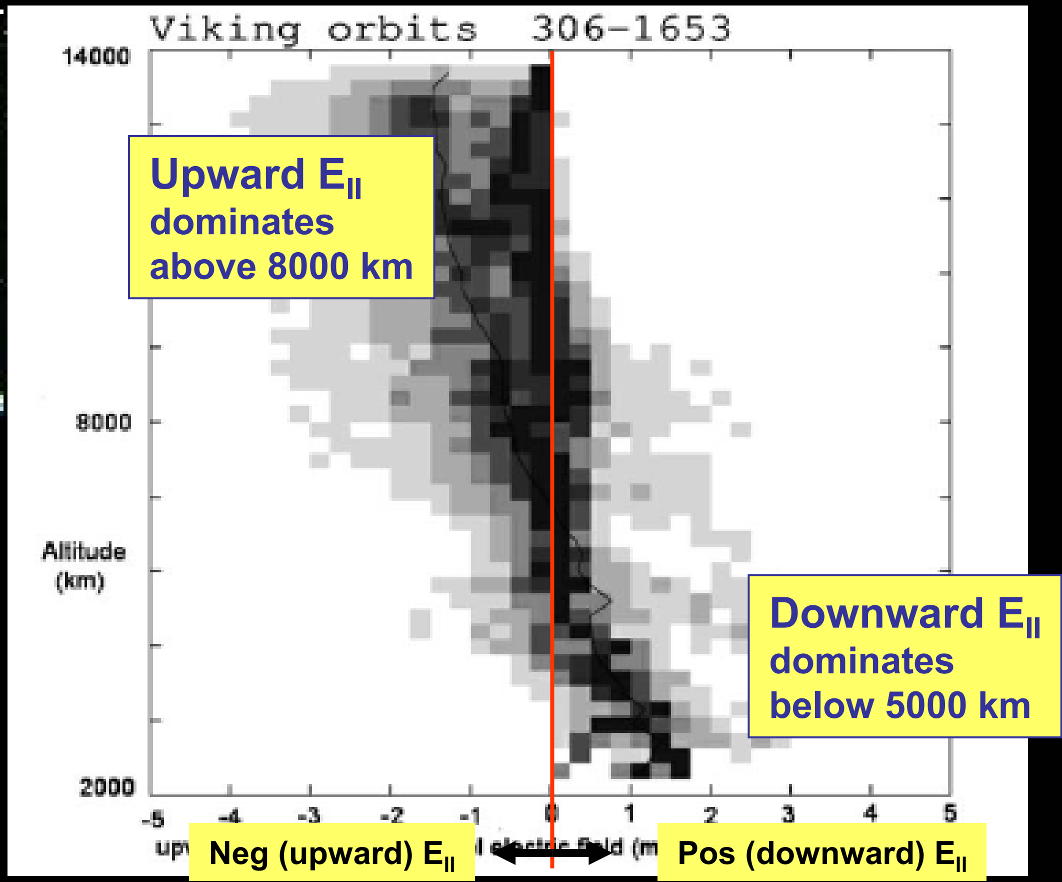
Black auroral curls in diffuse aurora



At diffuse & discrete aurora boundary

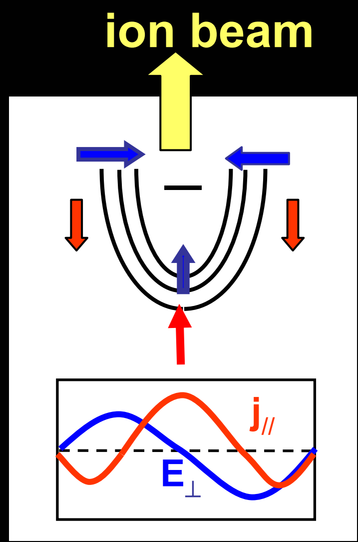
Viking Auroral Electric Fields

800 km-13600 km
Statistical Study of Parallel Electric Field



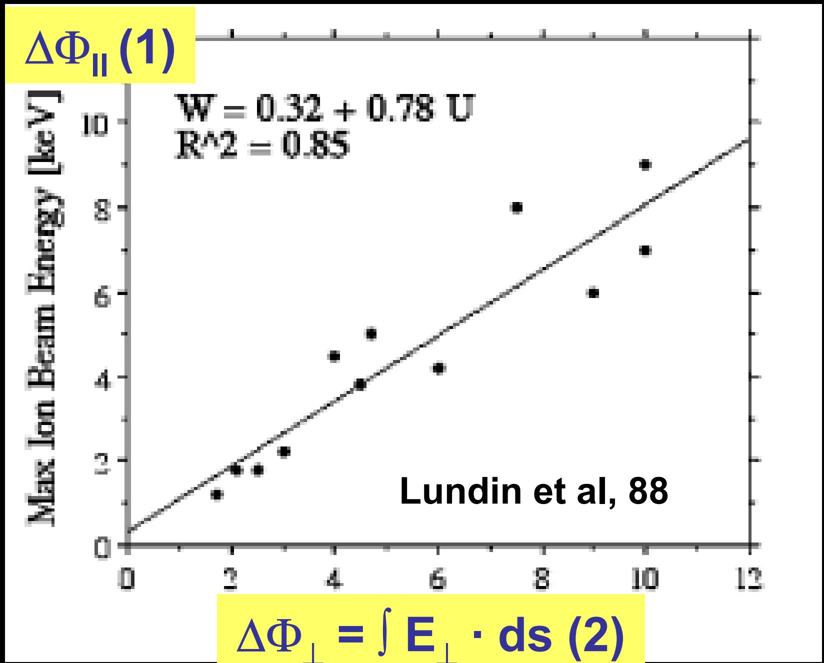
Viking Auroral Electric Fields

Evidence for quasi-static potential drops below Viking



Estimates of $\Delta\Phi_{II}$ using 3 different methods

1. $\Delta\Phi_\perp = \int E_\perp \cdot ds$
2. from Electron Loss Cones
3. from upward ion beam energy



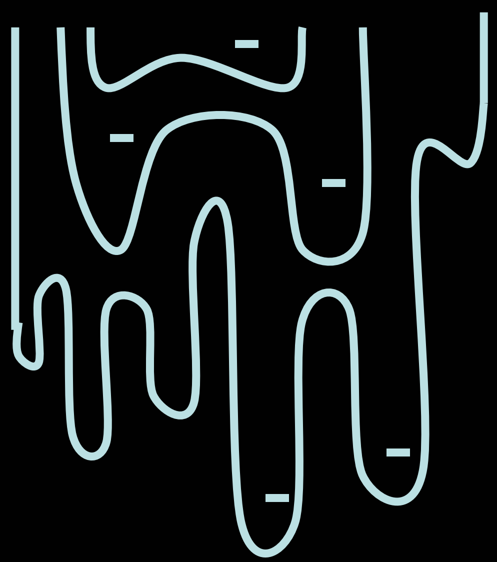
Block et al, 90

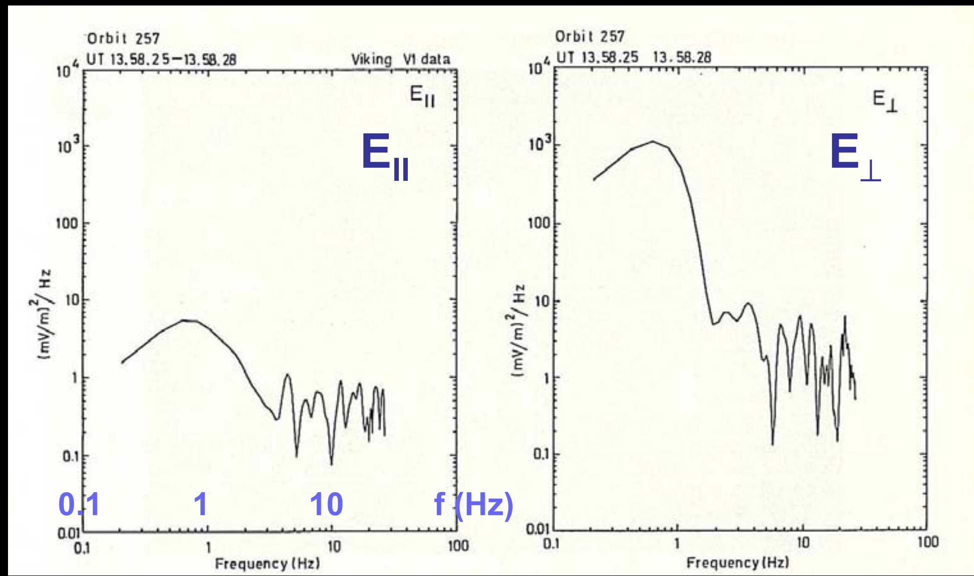
Orbit	Altitude, km	$E(\text{keV})/LC^\circ$	$\Delta\Phi_{II}^{LC}$ (2)	$\Delta\Phi_{II}^{IB}$ (3)
266	8,157	0.15/41	0.58	0.85
		0.25/33	0.59	0.85
		0.28/32	0.60	0.85
		0.15/41	0.58	0.85
343	11,788	0.755/36	4.9	4.6
		0.37/55	5.0	4.6
343	11,865	0.73/21	1.34	1.4
		0.37/29	1.55	1.4
1169	9,192	0.97/18	0.30	0.4
		0.52/22	0.48	0.4
1169	9,151	0.52/58	1.0	0.65
		0.28/37	1.1	0.65
1169	8,496	0.91/32	2.1	1.9
		0.57/36	1.8	1.9
1169	8,451	0.91/32	2.1	1.6
		0.57/37	1.9	1.6
1169	8,410	0.85/21	0.43	0.55
		0.52/25	0.57	0.55
1169	8,361	0.85/21	0.42	0.5

Viking Auroral Electric Field

Low-Frequency Electric Field Fluctuations (f < 1 Hz)

Fluctuating, filamentary
U-shaped potentials



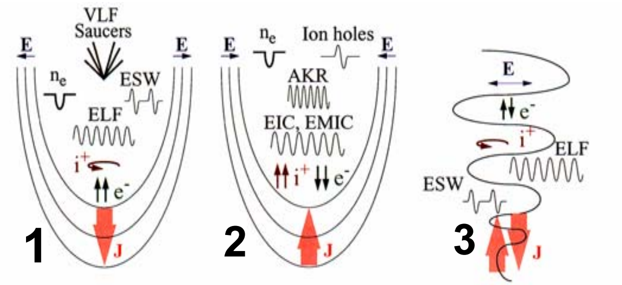


Questions / Implications of LFEFF's

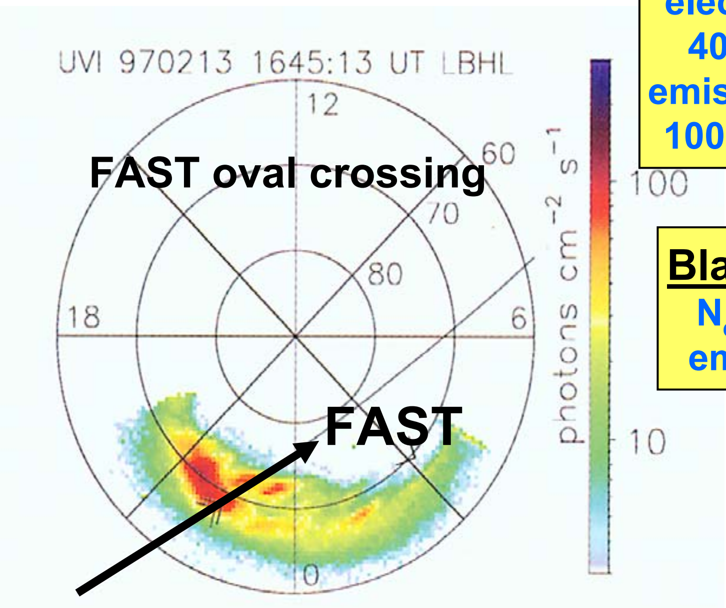
- spatial or temporal origin or both?
- E-field can be "ac" for ions (t_T^{ion} >> 1 s) & "dc" for electrons (t_T^{e} << 1 s)
- for $E_{\parallel}^{DC} < E_{\parallel}^{AC}$ ions & electrons can be accelerated in the same direction

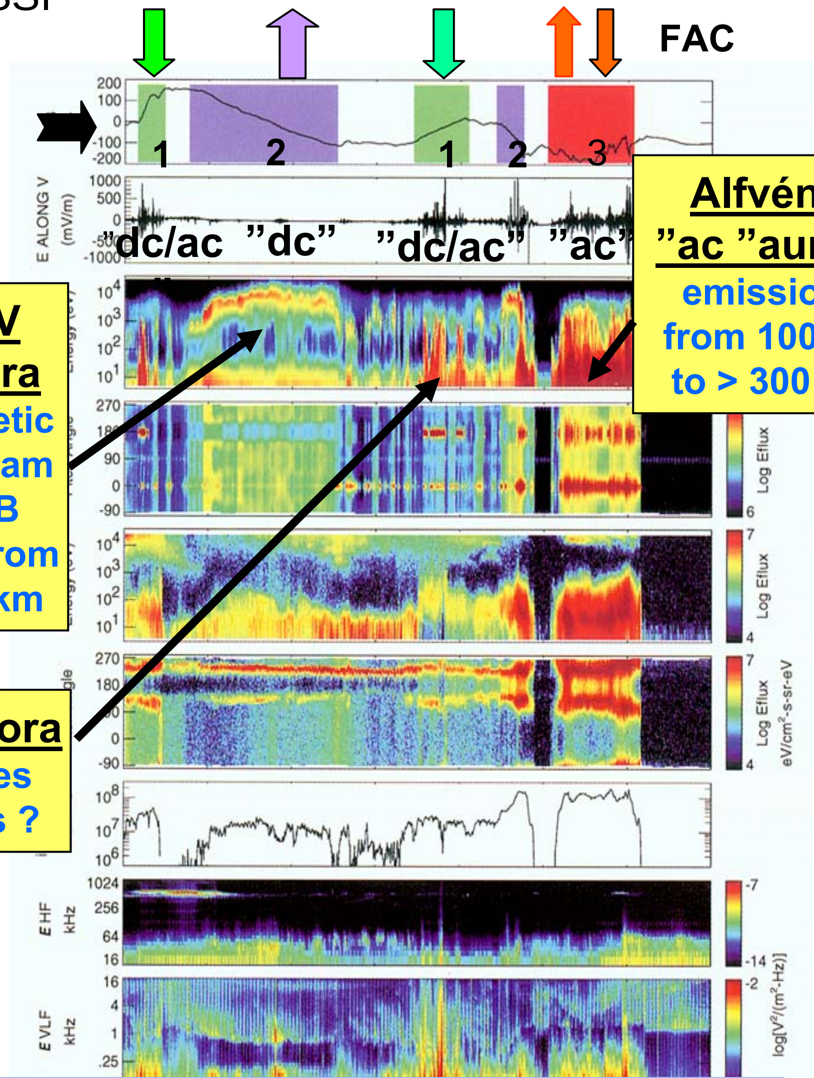
Classification of acceleration regions

From Auroral Plasma Physics Book, ISSI



3 main regions of acceleration





Inverted-V
"dc" aurora
Monoenergetic electron beam
400 km ⊥ B
emissions from 100 to 150 km

Black aurora
N_e- cavities
emissions ?

Alfvénic
"ac "aurora
emissions from 100 km to > 300 km

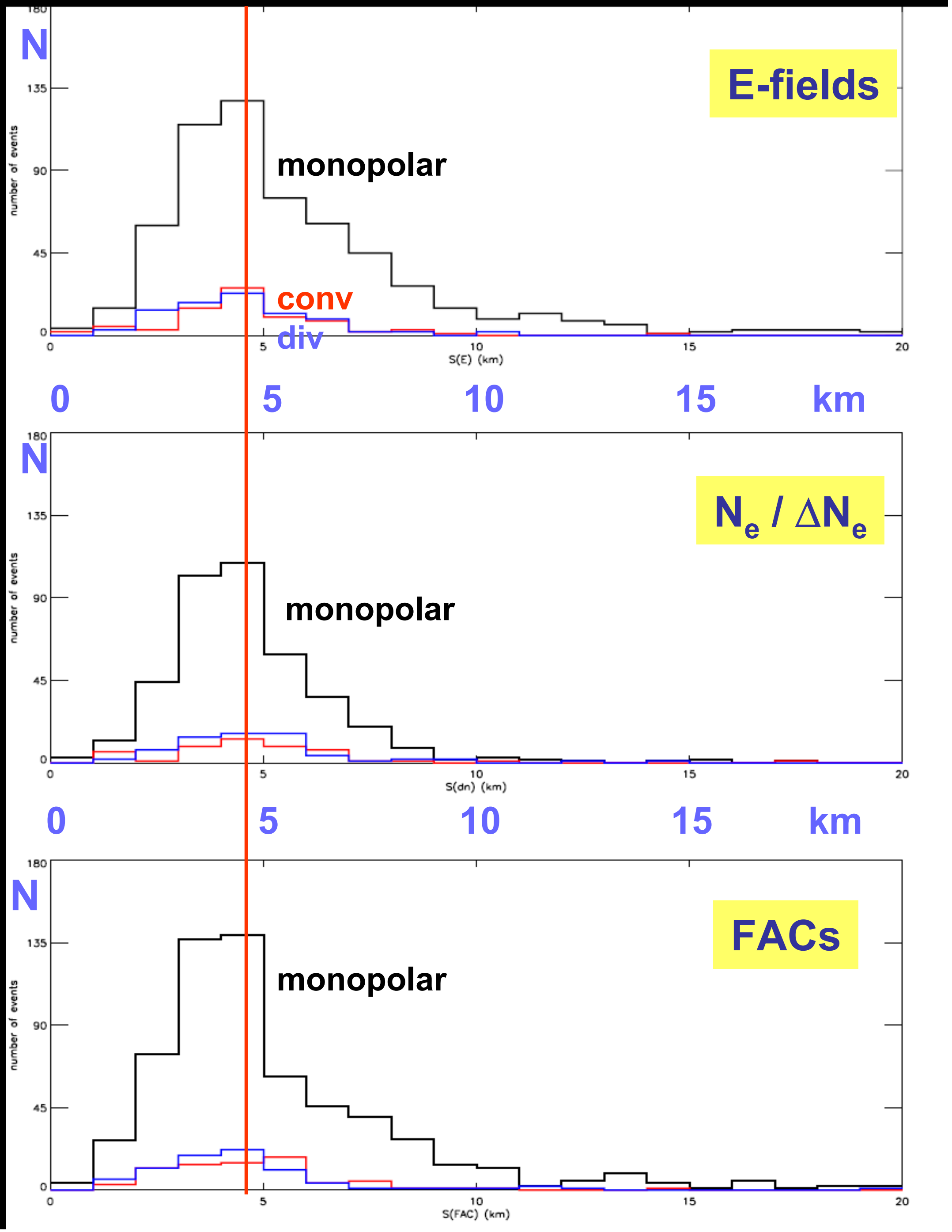
From altitude range & emission characteristics it should be possible to **distinguish between Inverted-V** and **Alfvénic aurora** !

2. High-Altitude Aurora Cluster results:

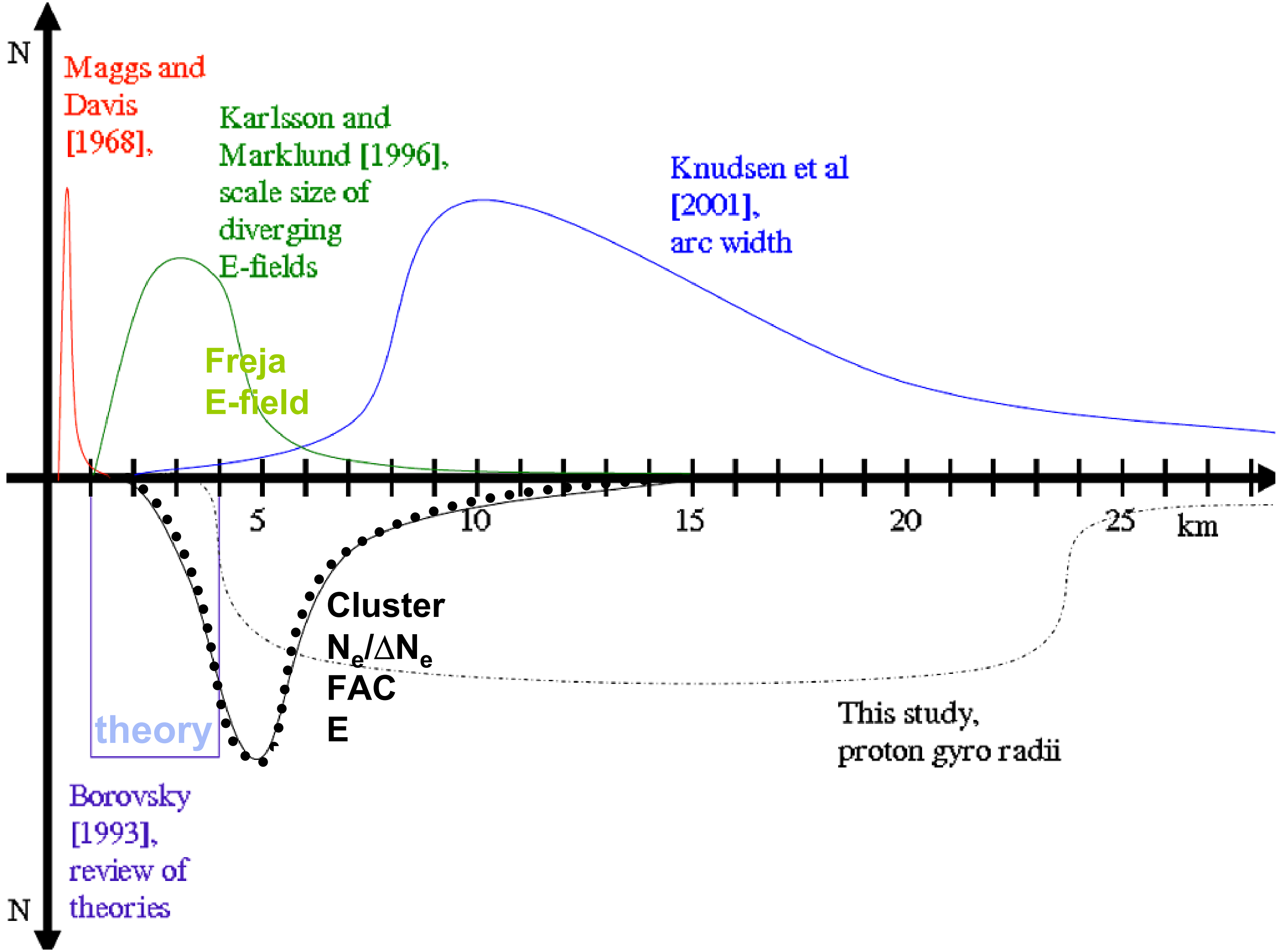
Statistical results on the scale sizes of monopolar & bipolar E-field events

- E-fields & associated
- N_e-gradients and
- FACs

Number of events peak at 4.5 km for all three parameters



Scale sizes of arcs & arc-associated E-fields



2. High-Altitude Auroral E-fields: Cluster

Characteristics of U^+ & U^- -potentials

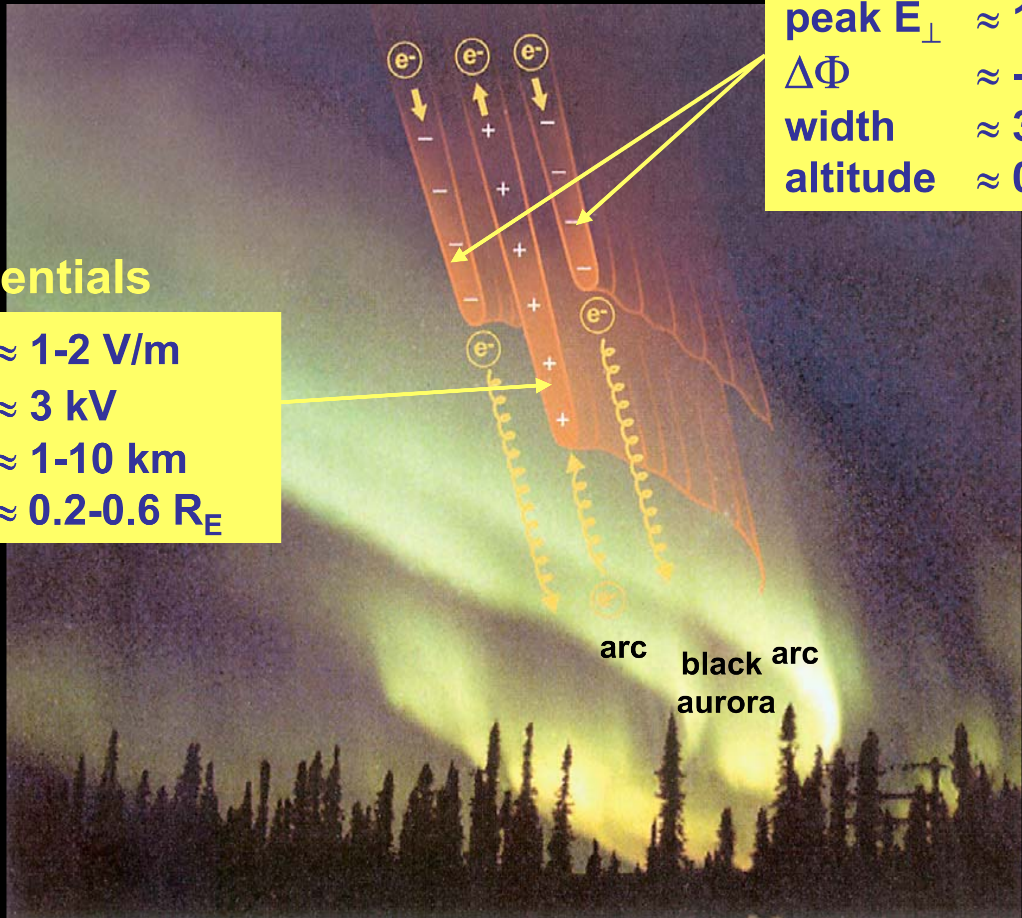
$E_\perp$ extends from the acceleration region up to and beyond 5 R_E

U^- -potentials

peak $E_\perp$	≈ 1 V/m
$\Delta\Phi$	≈ -10 kV
width	≈ 3-10 km
altitude	≈ 0.5-2 R_E

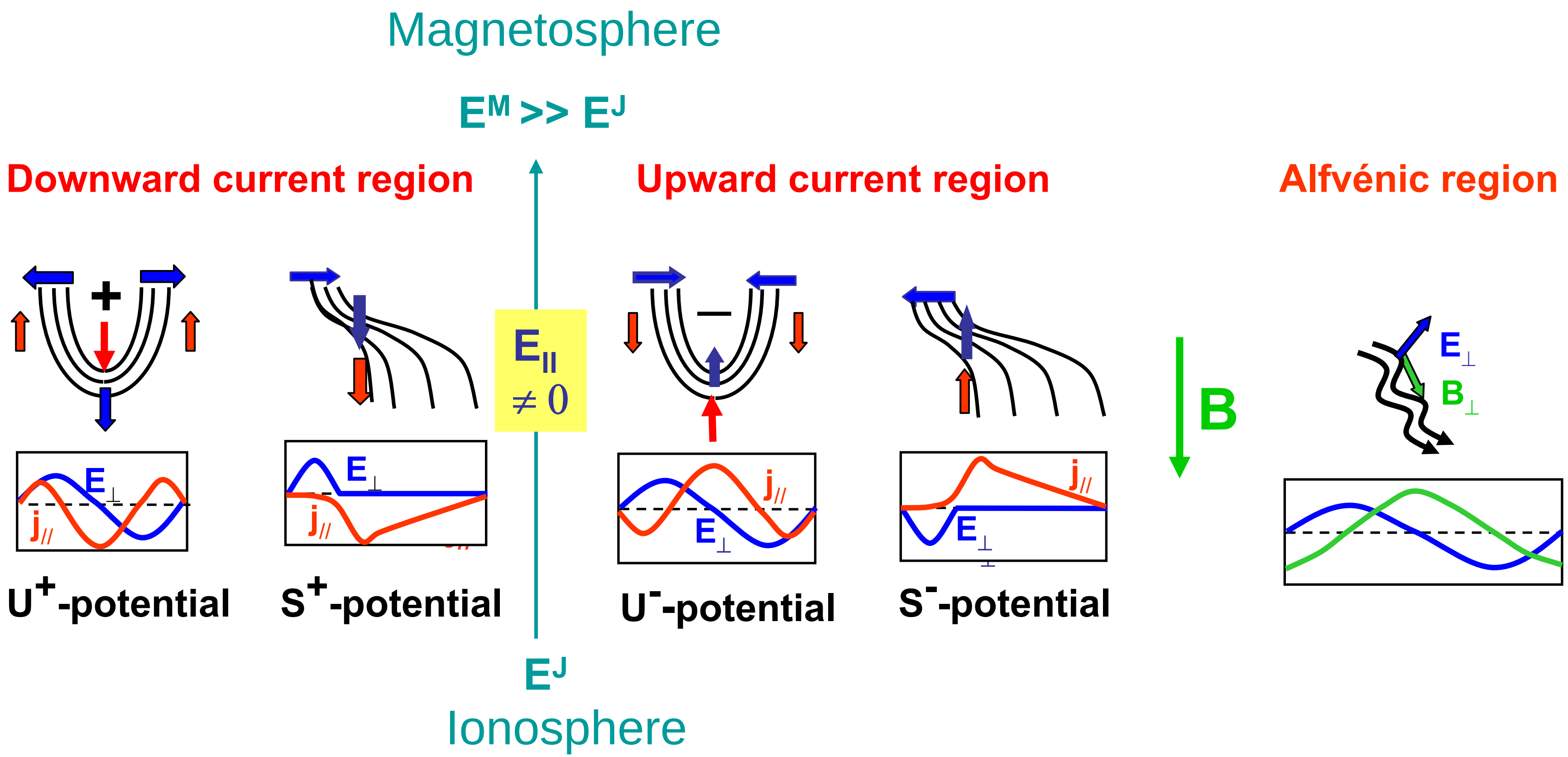
U^+ -potentials

peak $E_\perp$	≈ 1-2 V/m
$\Delta\Phi$	≈ 3 kV
width	≈ 1-10 km
altitude	≈ 0.2-0.6 R_E



2. High-Altitude Auroral E-fields: Cluster

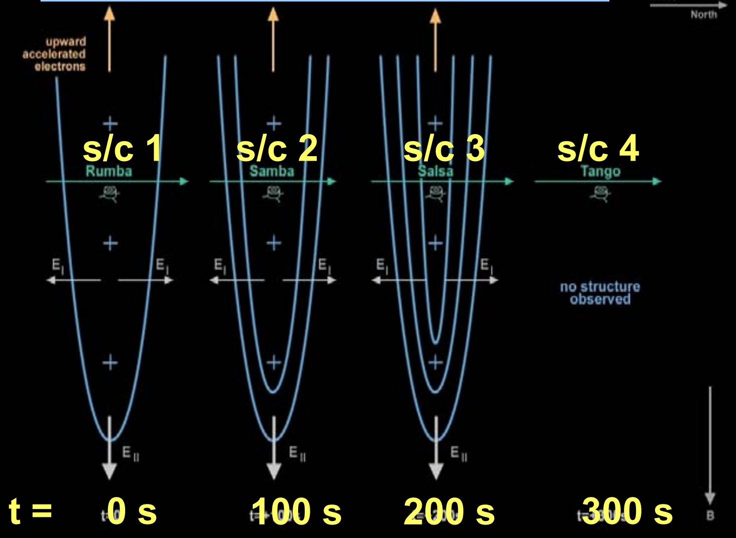
$U^{+/-}$ and $S^{+/-}$ -potentials identified in Cluster data



2. High-altitude auroral E-fields: Cluster

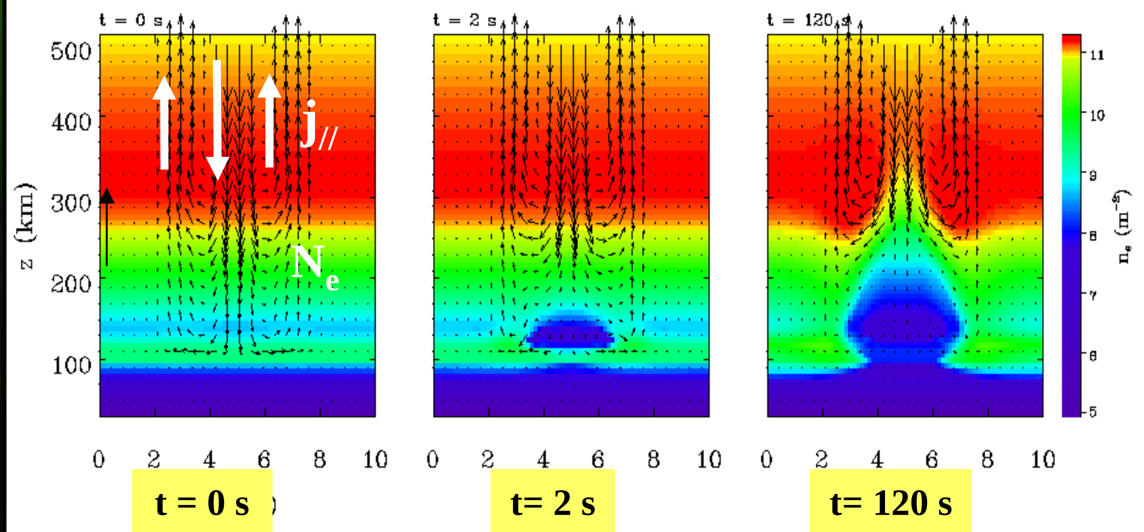
Similar time scale for growth of U^+-potential & E-region N_e hole

Growing U⁺-potential



Marklund et al., Nature 2001; Marklund et al 2004; 2005

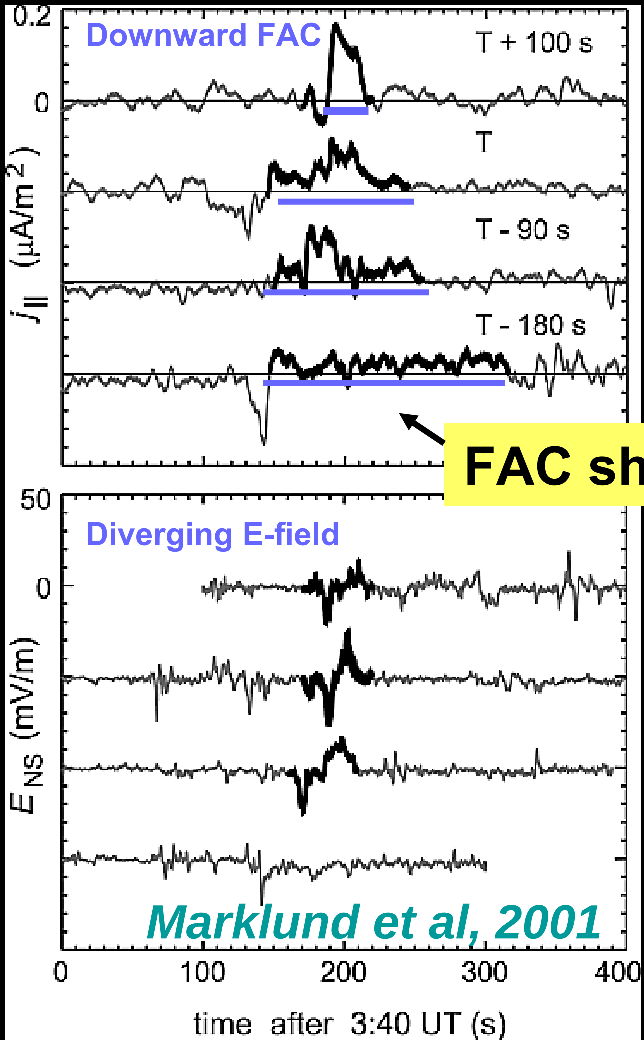
Simulated hole formation in ionosphere



2. High-Altitude Auroral E-fields: Cluster

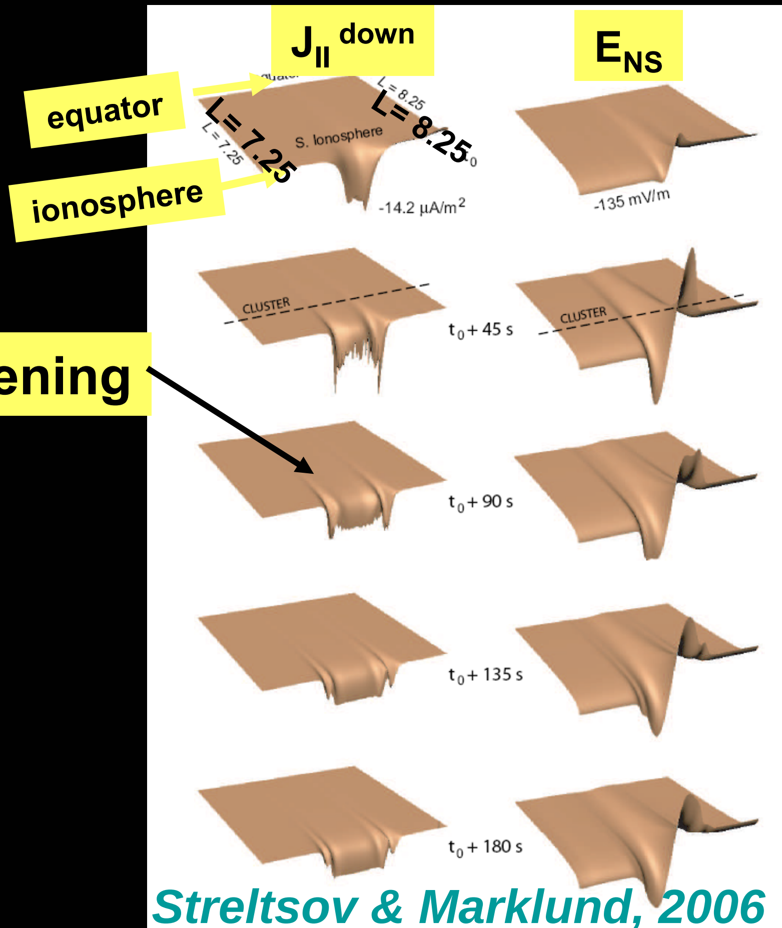
Widening of downward FAC sheet

Cluster event 2001-01-14

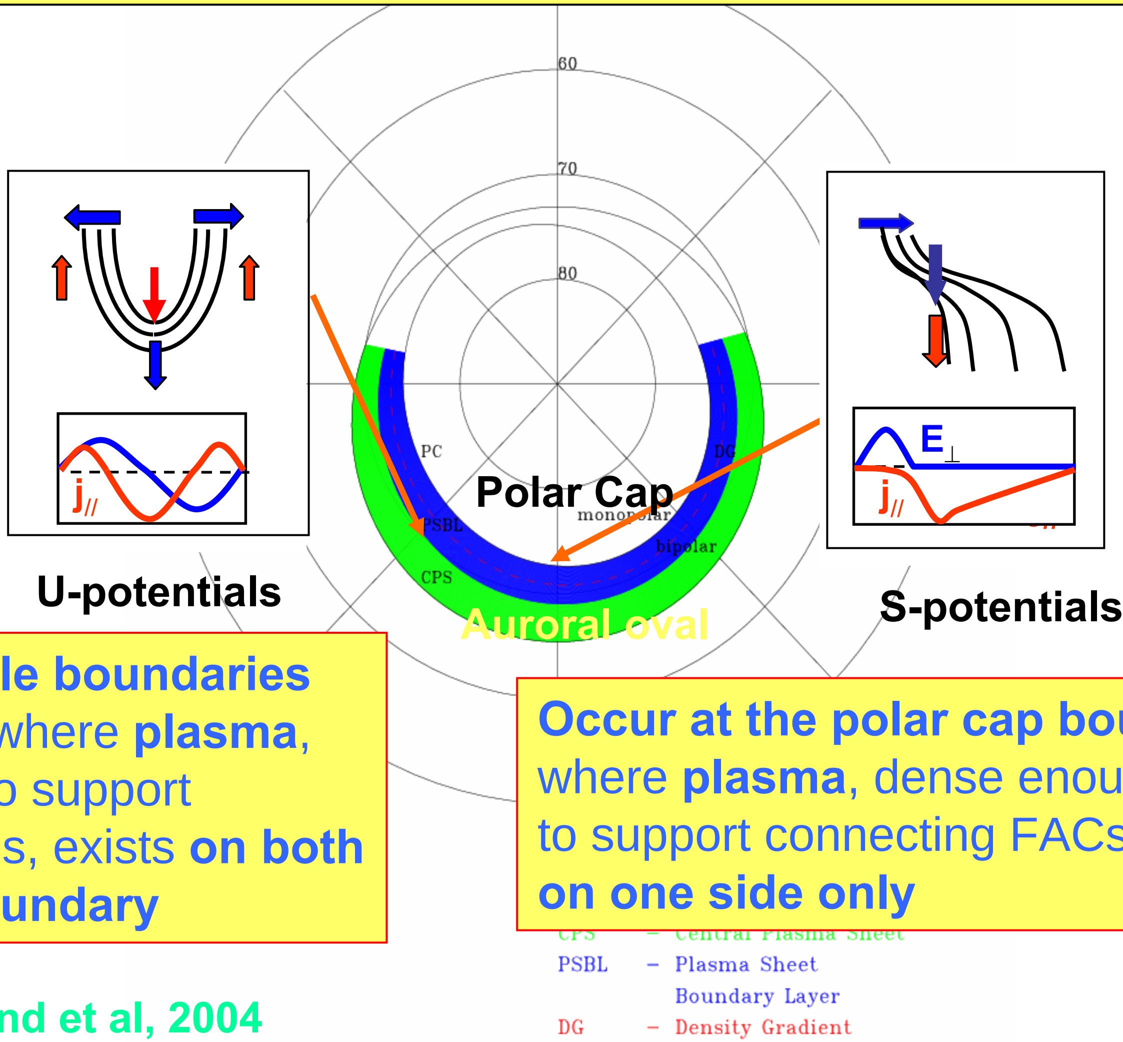


FAC sheet widening

Return current simulation



U- and S-potentials & Auroral Boundaries



Occur at particle boundaries within the PS, where **plasma**, dense enough to support connecting FACs, exists **on both sides of the boundary**

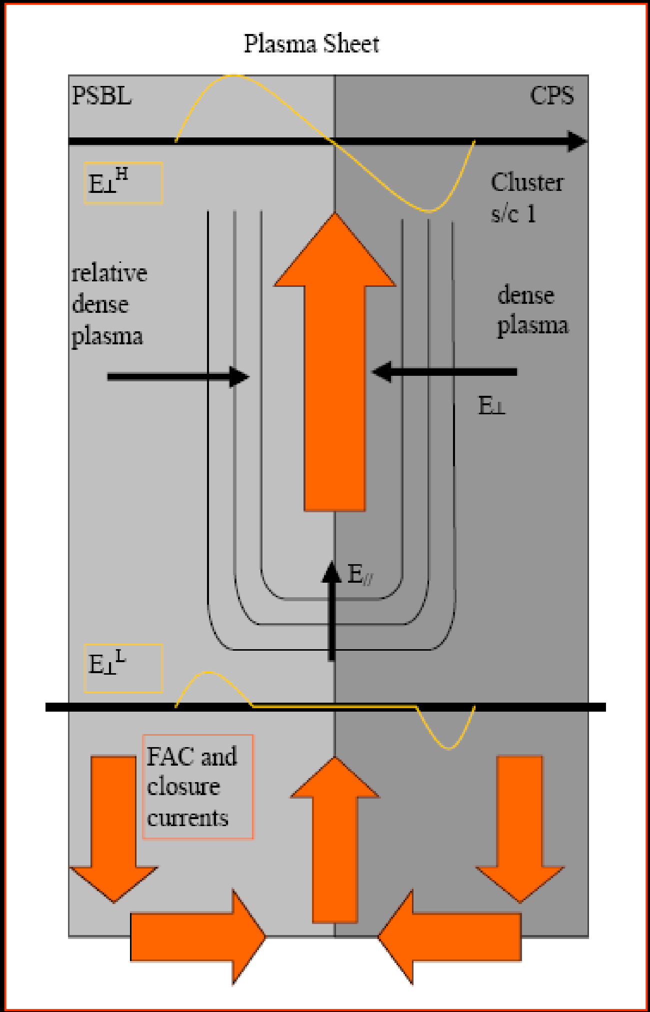
Occur at the polar cap boundary where **plasma**, dense enough to support connecting FACs, exists **on one side only**

Model by Marklund et al, 2004
Confirmed by Johansson et al, 2006

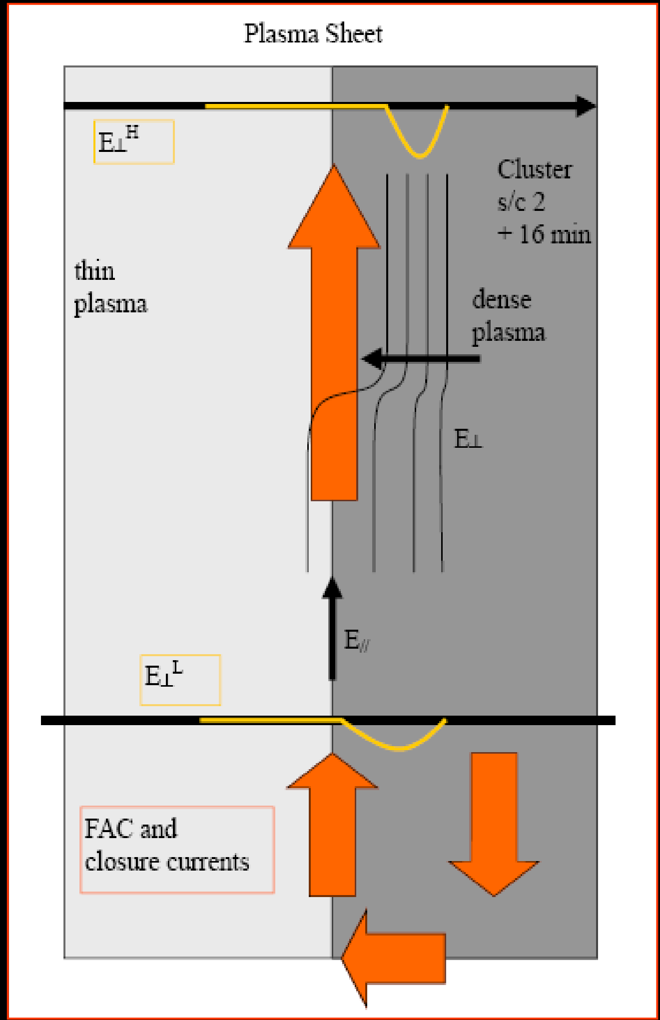
2. High-altitude auroral E-fields: Cluster

Potential- & FAC evolution as PSBL thins

Cluster s/c 1 $t = t_0$



Cluster s/c 2 $t = t_0 + 16$ min



Marklund et al, JGR, Jan 2007

3. Ionospheric coupling of auroral E- Fields & potentials

Approach

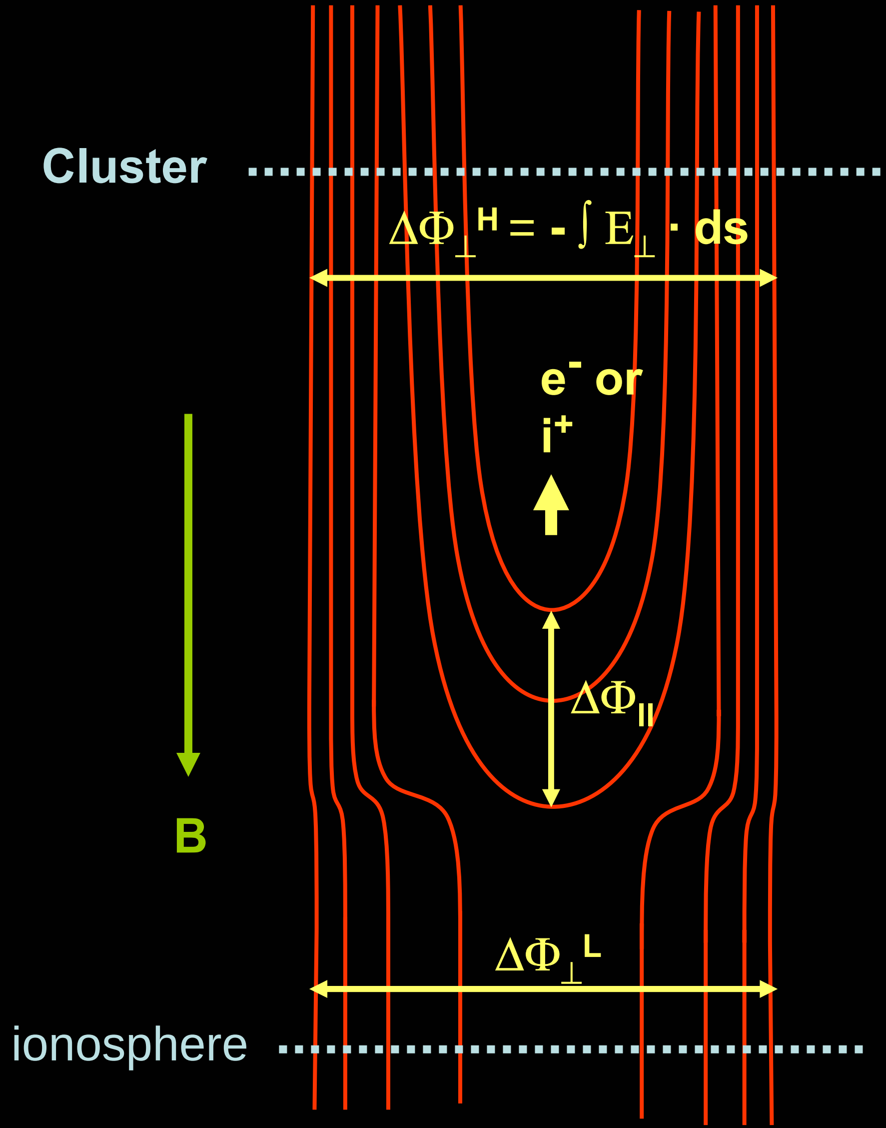
- $\Delta\Phi_{\perp} = -\int \mathbf{E}_{\perp} \cdot d\mathbf{s}$

- $\Delta\Phi_{\|}$ **from characteristic energy of :**

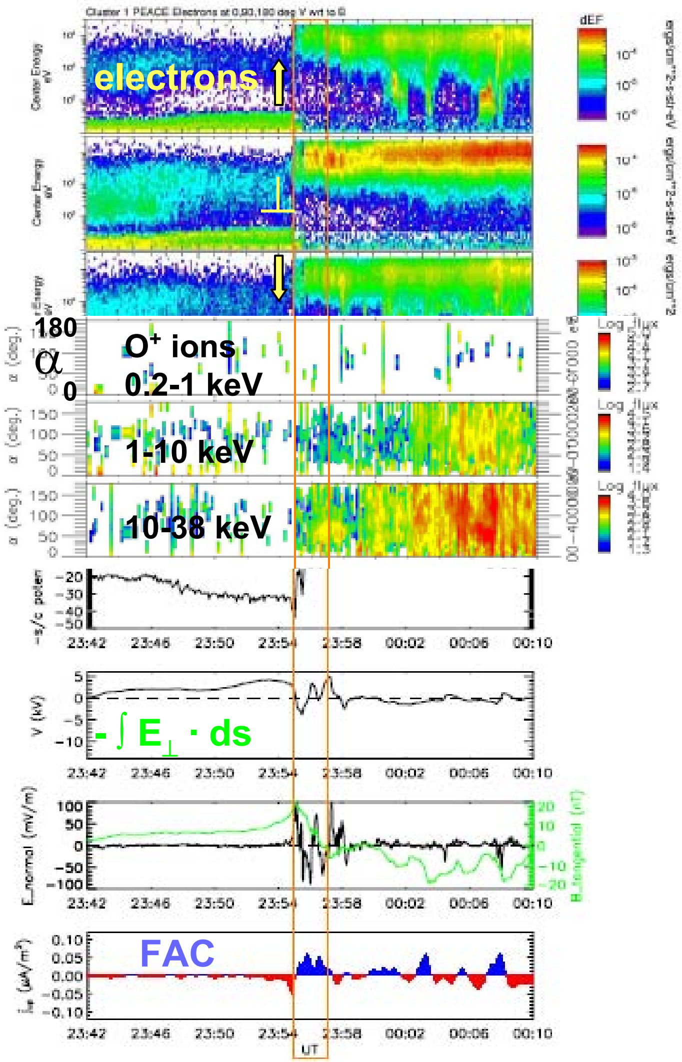
- **upward ions in upward FAC region**
- **upward electrons in downward FAC**

$$K = \Delta\Phi_{\|} / \Delta\Phi_{\perp}$$

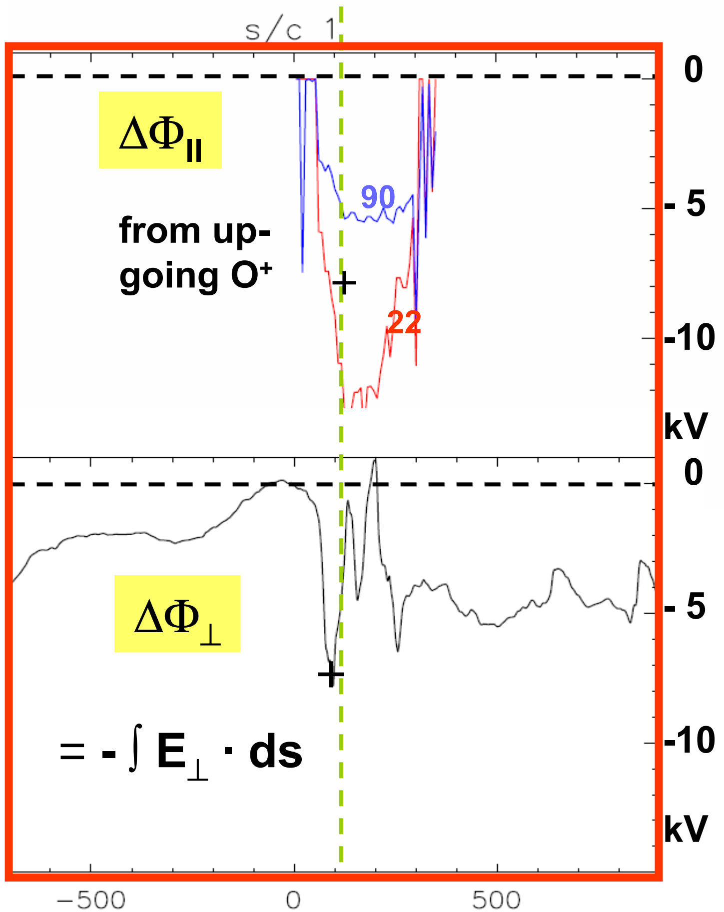
$k = 0$	coupling
$0 < k < 1$	partly coupling
$k = 1$	decoupling



Example: Cluster event 2003-05-03 upward FAC

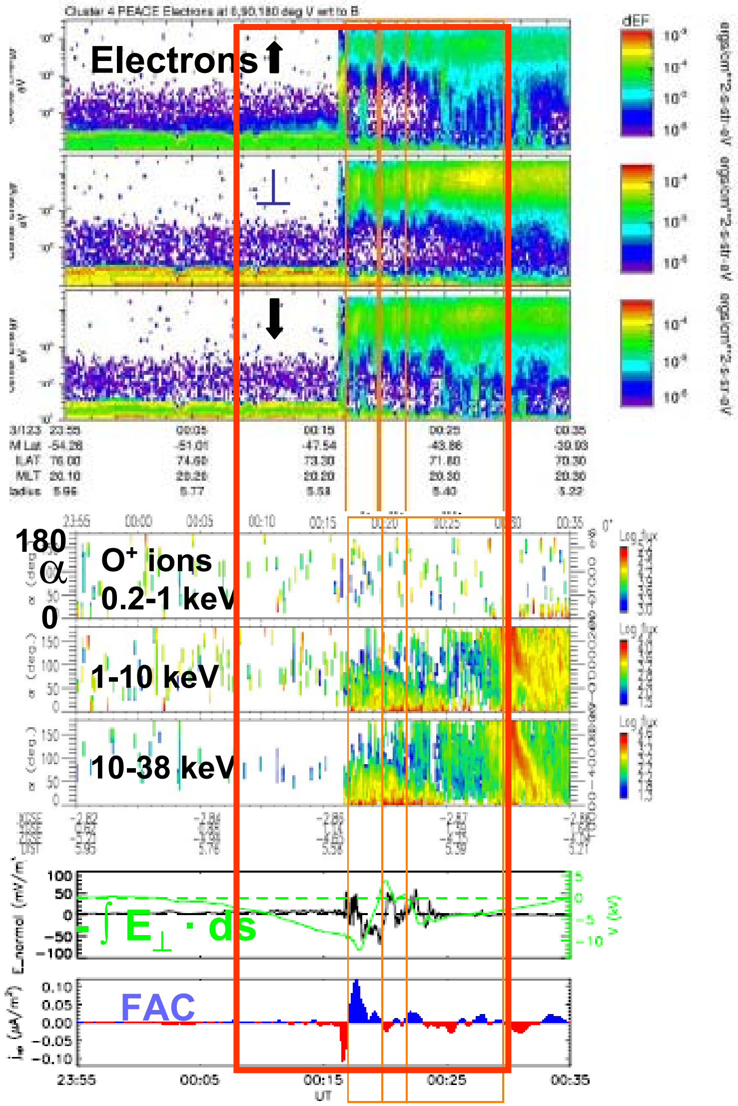


spacecraft 1

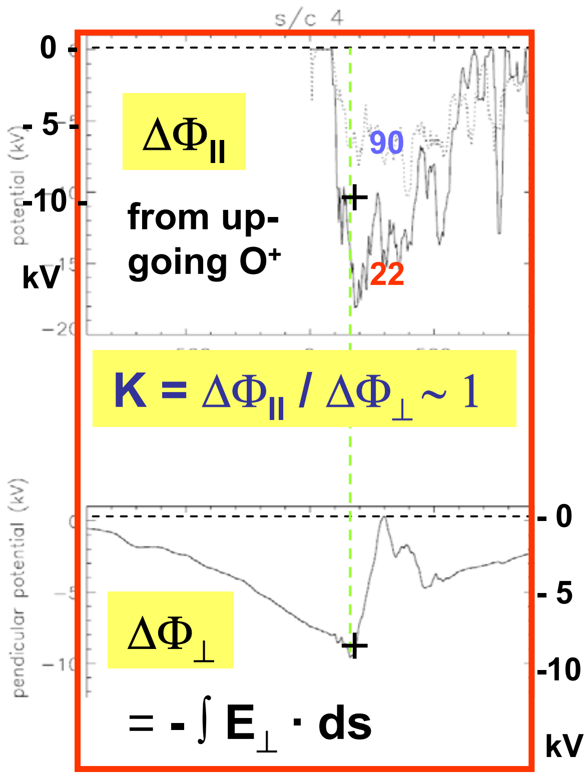


Decoupling, $\Delta\Phi_{||} \sim \Delta\Phi_{\perp}$

Example: Cluster event 2003-05-03   upward FAC



spacecraft 4



Decoupling, $\Delta\Phi_{||} \sim \Delta\Phi_{\perp}$

3. Ionospheric coupling of auroral E- Fields & Potentials: Results from initial Cluster event list

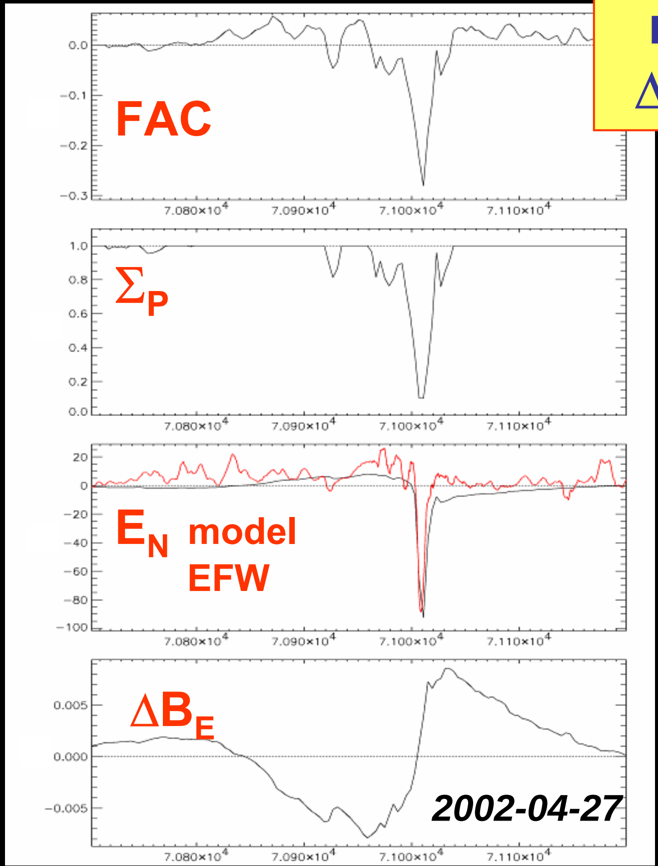
Decoupling dominates for small-scale E-fields & potentials !

Event date	2001 01-14	2001 02-14	2002 04-27	2002 05-19	2002 11-25	2003 02-28	2003 05-01	2003 05-03
MLT	03:30	00:20	20:00	20:00	05:30	00:00	20:00	23:30
Hem	NH	SH	SH	SH	NH	SH	SH	SH
Potential	U	U	S	S	U	S	U(1) S (2)	U
FAC up/down	**down**	**down**	**down**	**down**	**down**	**down**	**up**	**up**
E-field peak (V/m)	0.35	1.5	1.7	0.45	0.03	0.07	0.82	0.05-0.1
Scale (km)	15	8 (2)	1.5 (2,4) 1.0 (3)	2 (1)	1.6 (1)	4.7 (1)	3.0 (1,2,3) 3.2 (4)	10 (2,4) 5 (1)
s/c	1,2,3	1,2,3,4	2,3,4	1,2,3,4	1	1	1,2,3,4	1,2,4
$\Delta\Phi_{\perp}$ (kv)	2	3	3	0.2-0.3	0.6	12	10	8 (1) 12 (4)
$\Delta\Phi_{II}$ (kv)	2	No data	3	0.2	0.5	2-6	10	8 (1) 12 (4)
K = $\Delta\Phi_{II} / \Delta\Phi_{\perp}$	1	?	1	0.7-1	0.9	0.2-0.5	1	1

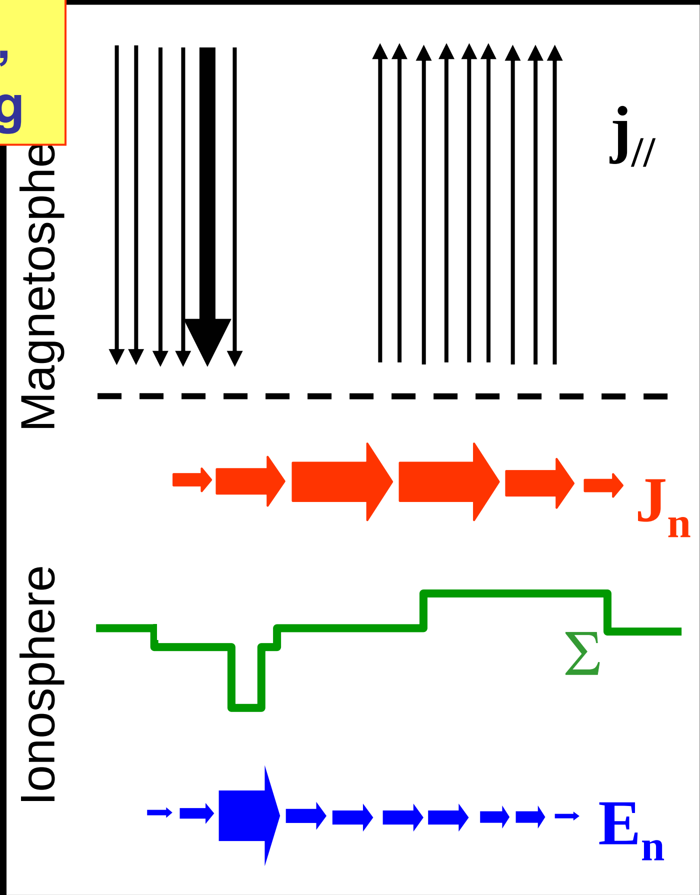
3. Ionospheric Coupling of Auroral E-Fields

E– $j_{||}$ correlation in downward FACs *(Karlsson et al, 2007)*

E-field adjusts to N_e & Σ_P cavities
no acceleration,
$\Delta\Phi_{//} = 0$: coupling



Cluster - model comparison



scenario

3. Ionospheric Coupling of Auroral E-fields & Potentials

FAST results for downward FACs *(Hwang et al, 2006)*

$\eta = d\varepsilon_{ce} / E_{av}$

Hwang et al, 2006

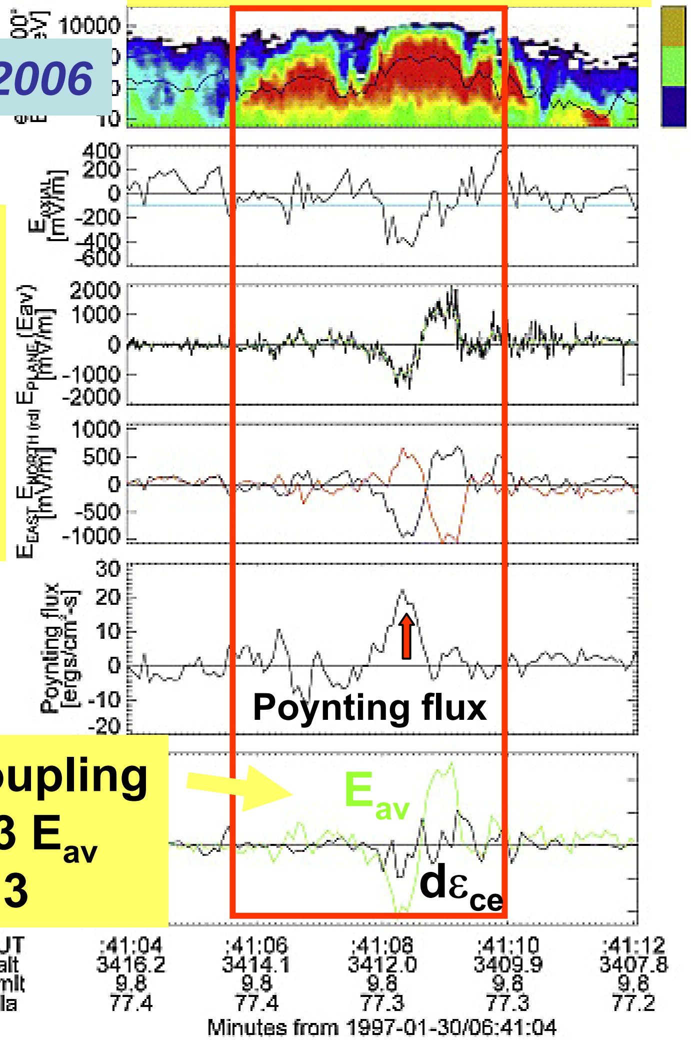
Our study

$k = \Delta\Phi_{\parallel} / \Delta\Phi_{\perp}$

$e\,\Delta\Phi_{\parallel} = \varepsilon_{ce}$

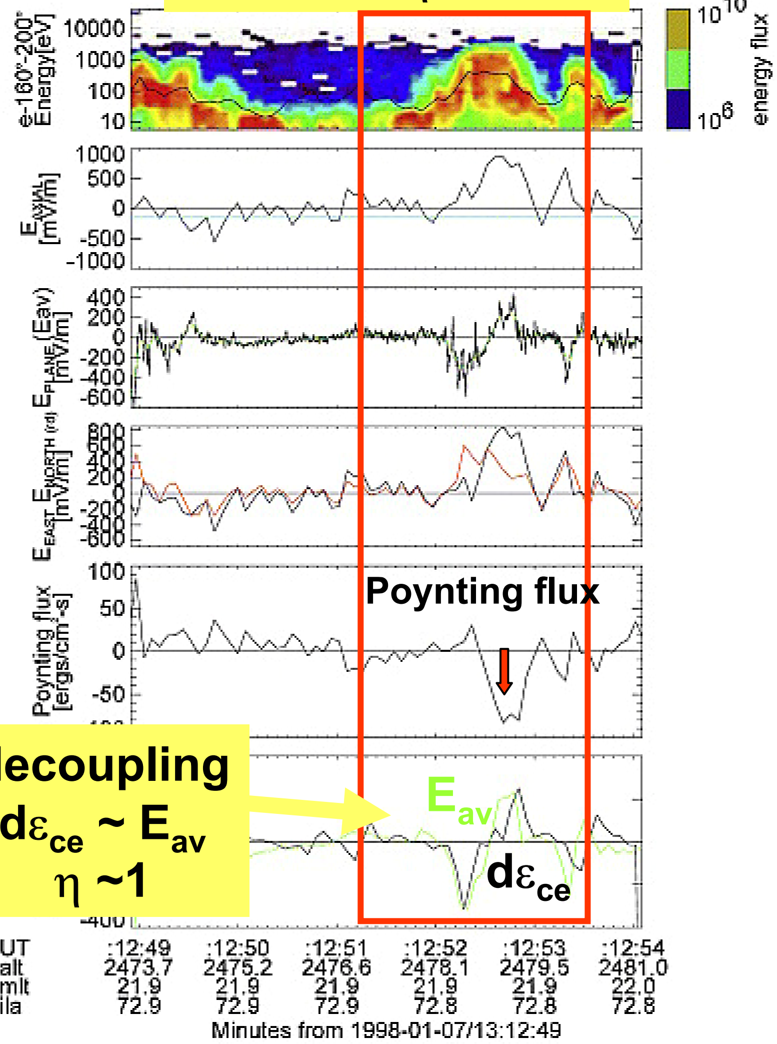
$\Delta\Phi_{\perp} = -\int E_{av} \cdot ds$

Sheetlike structures
$0.1 < \eta < 0.4$



Part. decoupling
$d\varepsilon_{ce} \sim 1/3\, E_{av}$
$\eta \sim 0.3$

Curved structures
$0.5 < \eta < 1$



decoupling
$d\varepsilon_{ce} \sim E_{av}$
$\eta \sim 1$

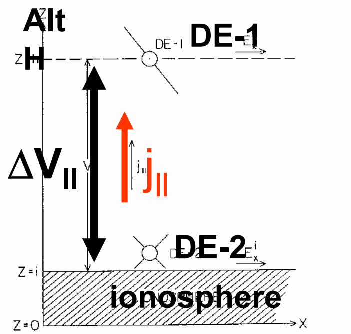
3. Ionospheric coupling of auroral E-Fields & Potentials

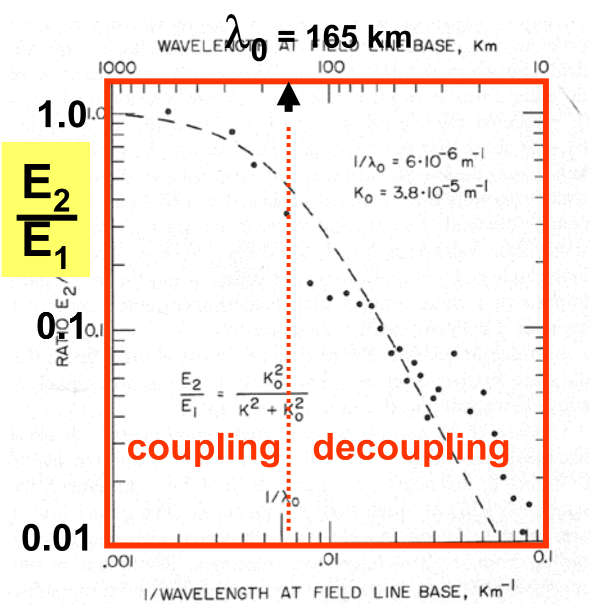
DE-1 (High) & 2 (Low) comparisons (*Weimer et al, 85)*

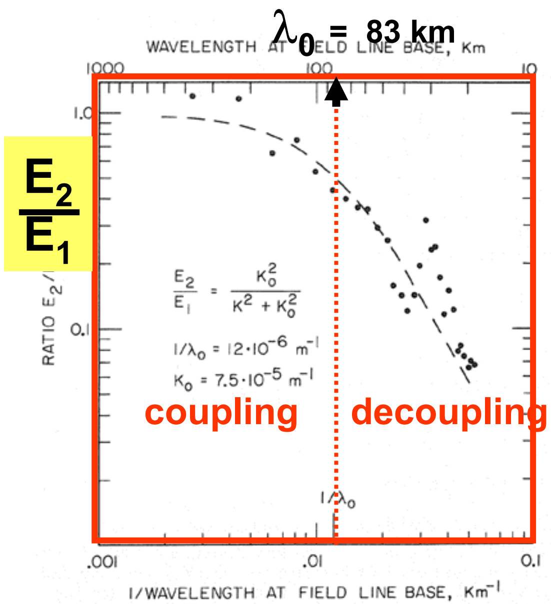
Scale-size dependent model for upward FACs

$j_{||} = - a \, V_{||}$ linear I-V relation, applicable to upward FACs

$\lambda_0 = 2 \pi (\Sigma_P / a)^{1/2}$ $E_2 / E_1 = (1 + (\lambda_0 / \lambda)^2)^{-1}$







SUMMARY

1. Low-and Medium Altitude Auroral E-fields & Potentials

Rocket results

$E_{arc} = E_{amb} + E_{pol}$, correlation & anticorrelation arcs, arc classification

Freja results

km-scale inv-V's, div E & return current Charact, wave heating of ions

Viking results

average $E_{||}$ vs altitude, LFE-fluctuations, $\Delta\Phi_{||}$ & $\Delta\Phi_{\perp}$ estimates

2. High-Altitude Auroral E-fields & Potentials Cluster results

- Scale sizes of E-fields, Ne-gradients, and FACs peak at 4.5 km
- Characteristics of U^+ & U^- -potentials
- S / U- potentials located at sharp / soft PS-boundaries
- Evolution of U^+ -potential & N_e- hole closely linked
- Widening of downward FAC sheet
- Potential- & FAC change as PSBL becomes thinner

3. Ionospheric coupling of auroral E- Fields & potentials

• Approach to study the coupling:	calculate	$k = \Delta\Phi_{||} / \Delta\Phi_{\perp}$
• Results from Cluster events:	decoupling	$k = 1$
• Correlation E – $j_{||}$ in downward FACs	coupling	$k = 0$
• FAST results for downward FACs	partly coupling	$0 < k < 1$
• DE-1 & 2 comparisons	coupling	$\lambda > \lambda_0$