Auroral ionospheric plasma processes

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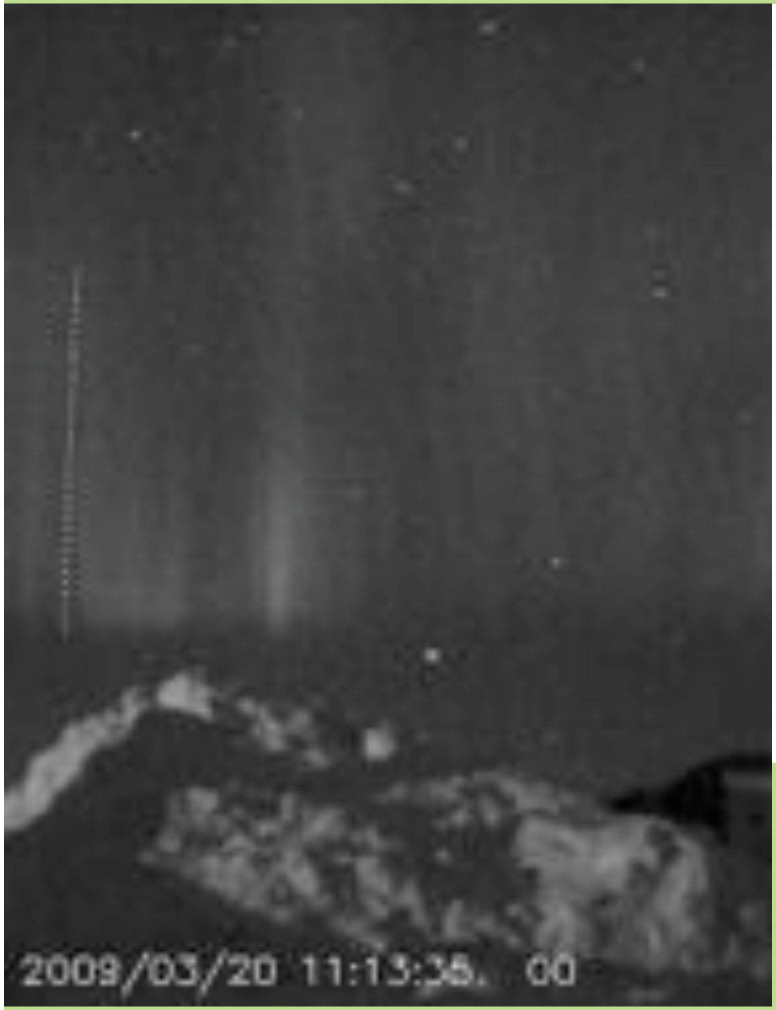
Dartmouth College

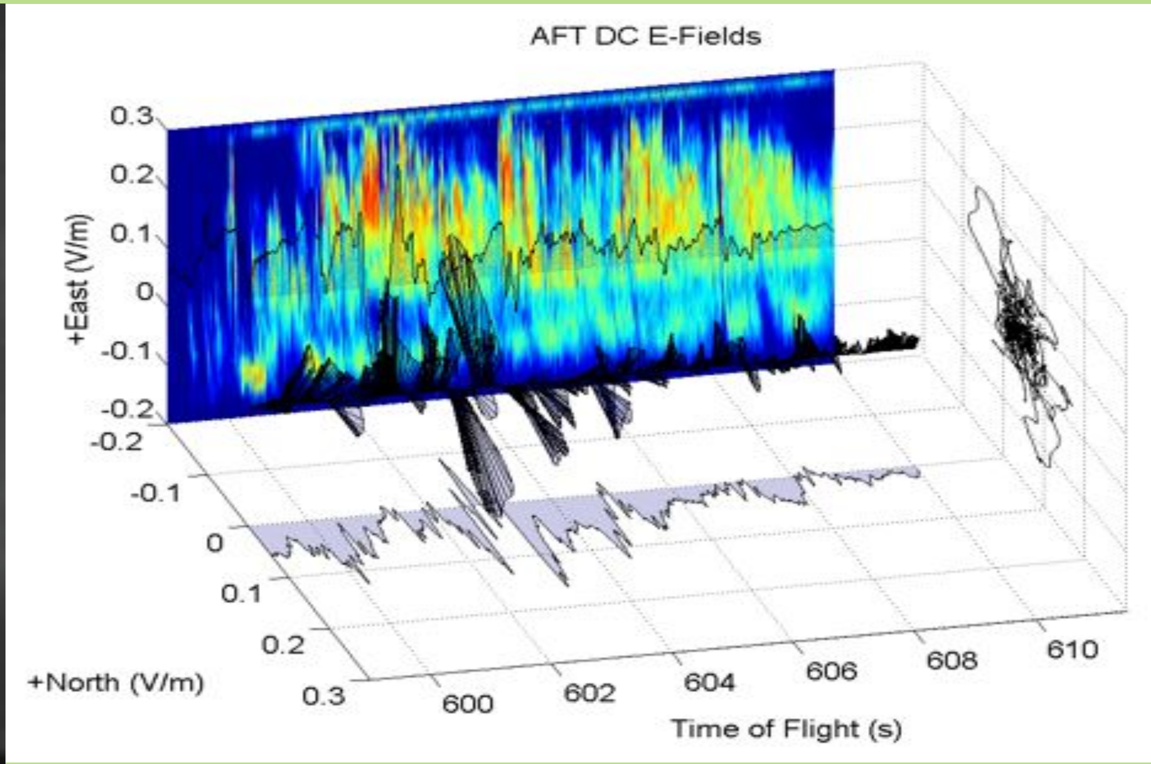
Movie by Mark Conde, UAF/GI

MICA rocket, FPI, PFISR, ASC

Plasma School, August 2012, Boston U

Questions about auroral drivers





Questions about ionospheric response

"…no technology barriers that would prevent making temperature and wind measurements of the neutral atmosphere well into the thermosphere to 1000 km. This capability would open an entirely new region of chemistry and atmospheric modeling..."

- Auroral-driven ionosphere-thermosphere responses
- Ion fountain, sawtooth events, neutral upwelling, charge exchange, Alfvenic feedback, ion outflow….
- Here: consider details of responses to auroral drivers

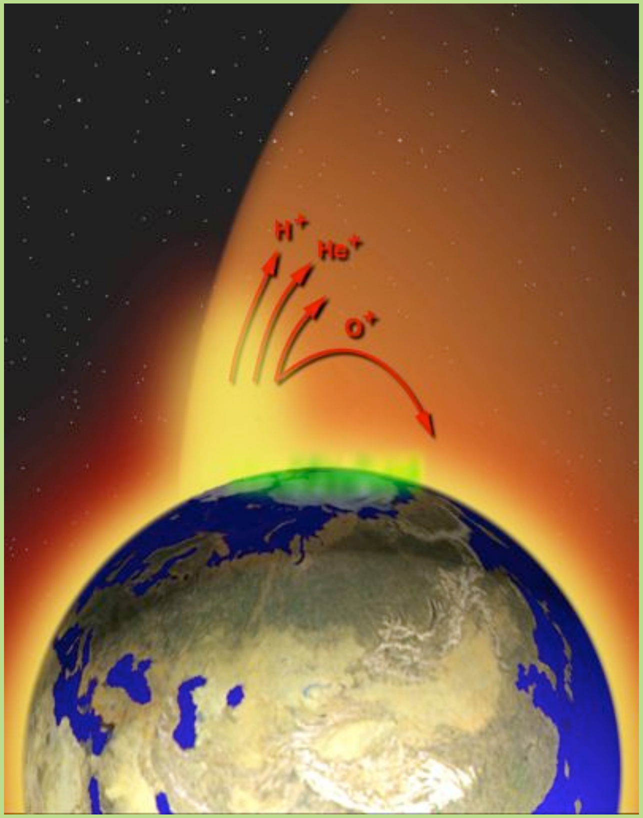


Image by Tom Moore, GSFC

"Scifer Cleft ion fountain"

Questions about ionospheric feedbacks

- Streltsov/Lotko Ionospheric Alfven Resonator
- Filamentation of downward current region
- Predicts strong distortion of ionospheric footpoint

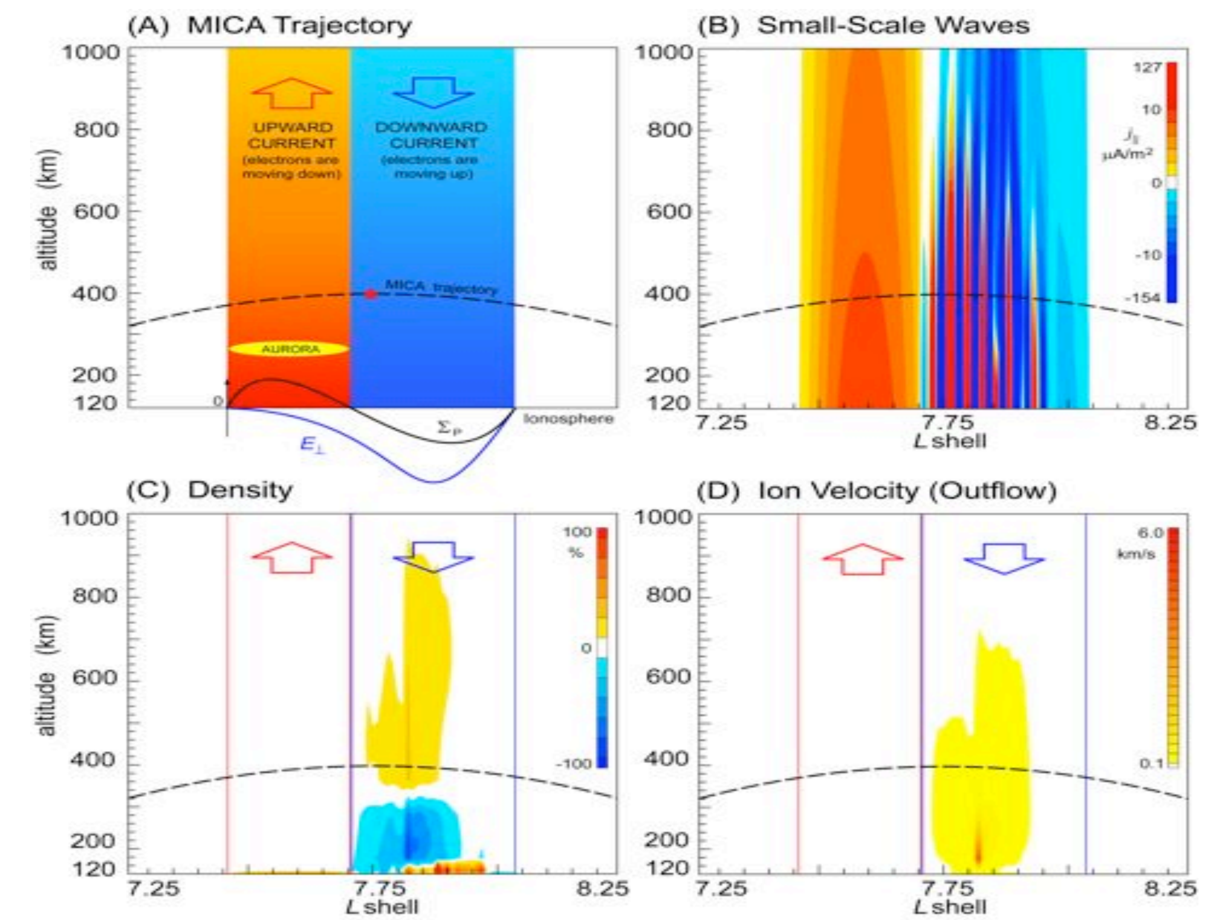
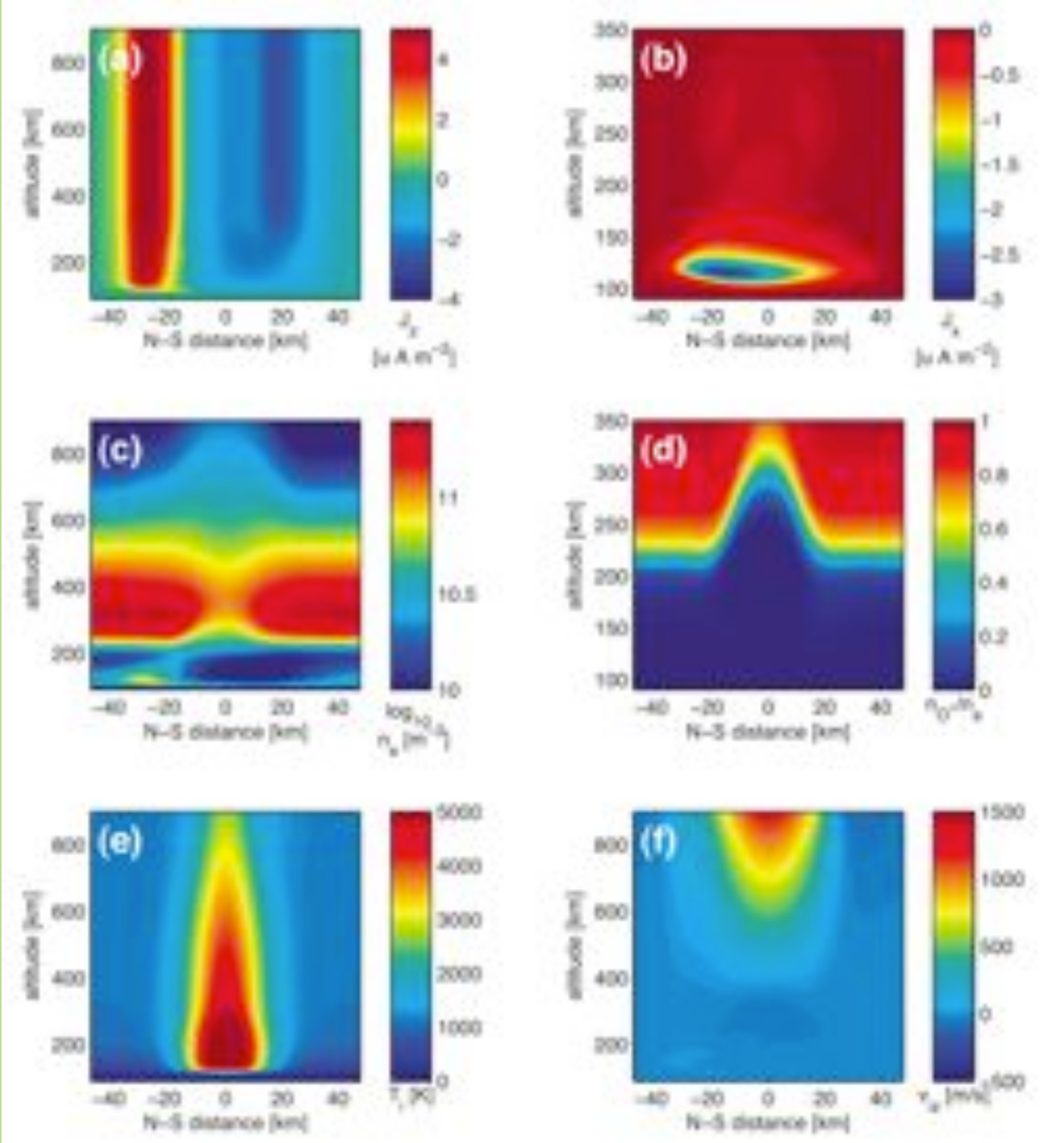


Figure 1. Modeled response of the ionosphere to the ionospheric feedback instability producing structured FAC in the downward-current region.

Questions about ionospheric structuring and dynamics

- Zettergren and Semeter, 2012
- Effects of composition and collisions
- 2D electrostatic



Introduction: Questions

- How to make an in situ map of auroral ionosphere?
- How to monitor response of a thermal plasma to drivers?
- Challenged assumptions:
  - $\Phi_{sheath} >> kT_e$
  - time and space variations
  - flows

Introduction: Goals

- Auroral zone: lower altitudes, lower energy coupling
- Conductivity gradients: source of current
- Shears and density gradients: wave growth
- Response of thermal ambient plasma:
  - Sheaths, charging, wakes, flows
- Multipoint array of sensorcraft:
  - Building a time-space map of ionospheric density evolution and structure

Outline

Jan Curtis

- Aurora
- Ionosphere
- Plasma
- Processes
- Instrumentation and measurements
- Swarms

Outline

- *Aurora*
  - **Morphology**
  - **E and J**
  - **Upward/downward/Alfvenic**
  - **Visible and f(v) types**
  - **Driver**
  - **Feedback**
- Ionosphere
- Plasma
- Processes
- Instrumentation and measurements
- Swarms

Jan Curtis

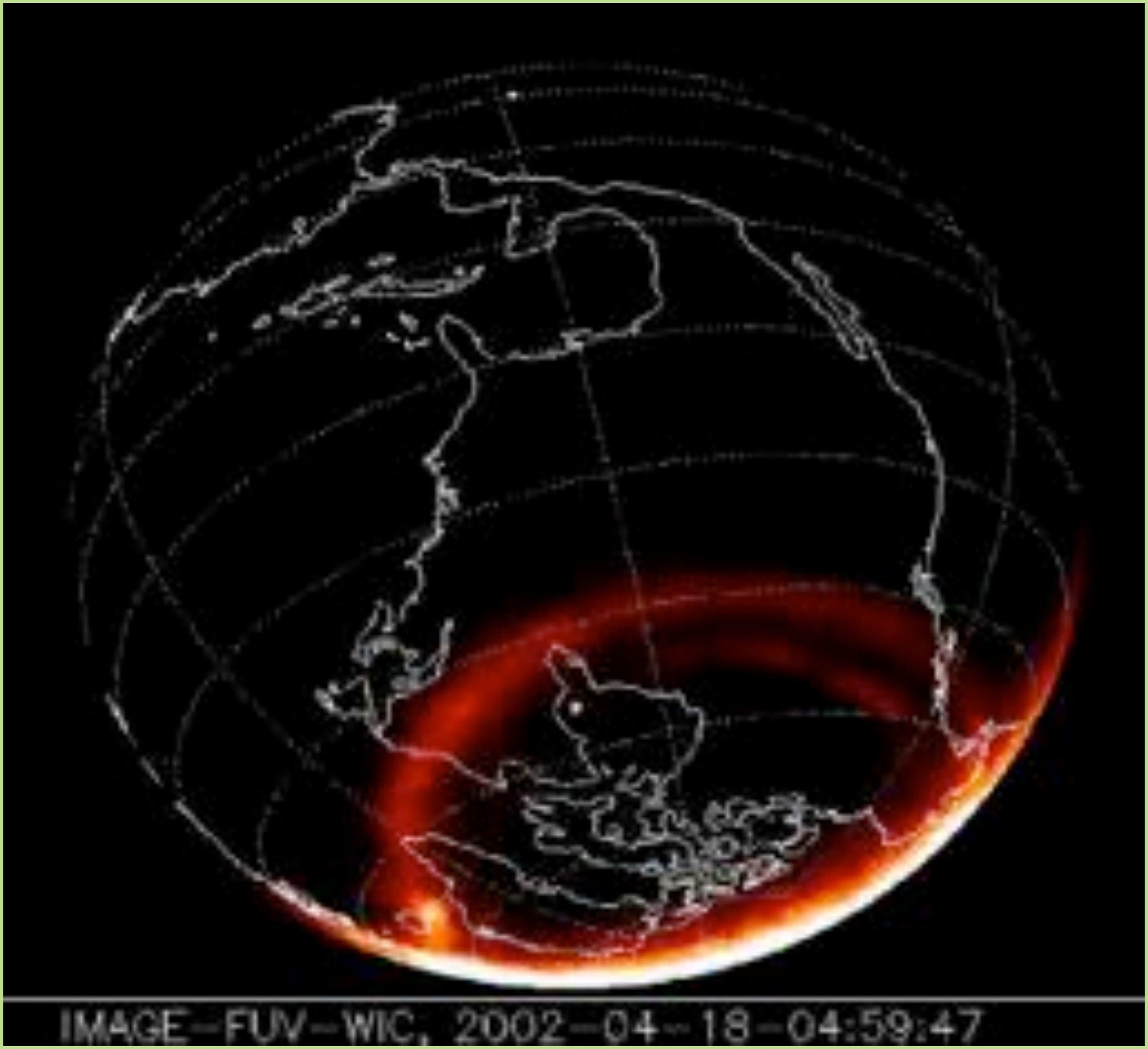


IMAGE-FUV-WIC, 2002-04-18-04:59:47

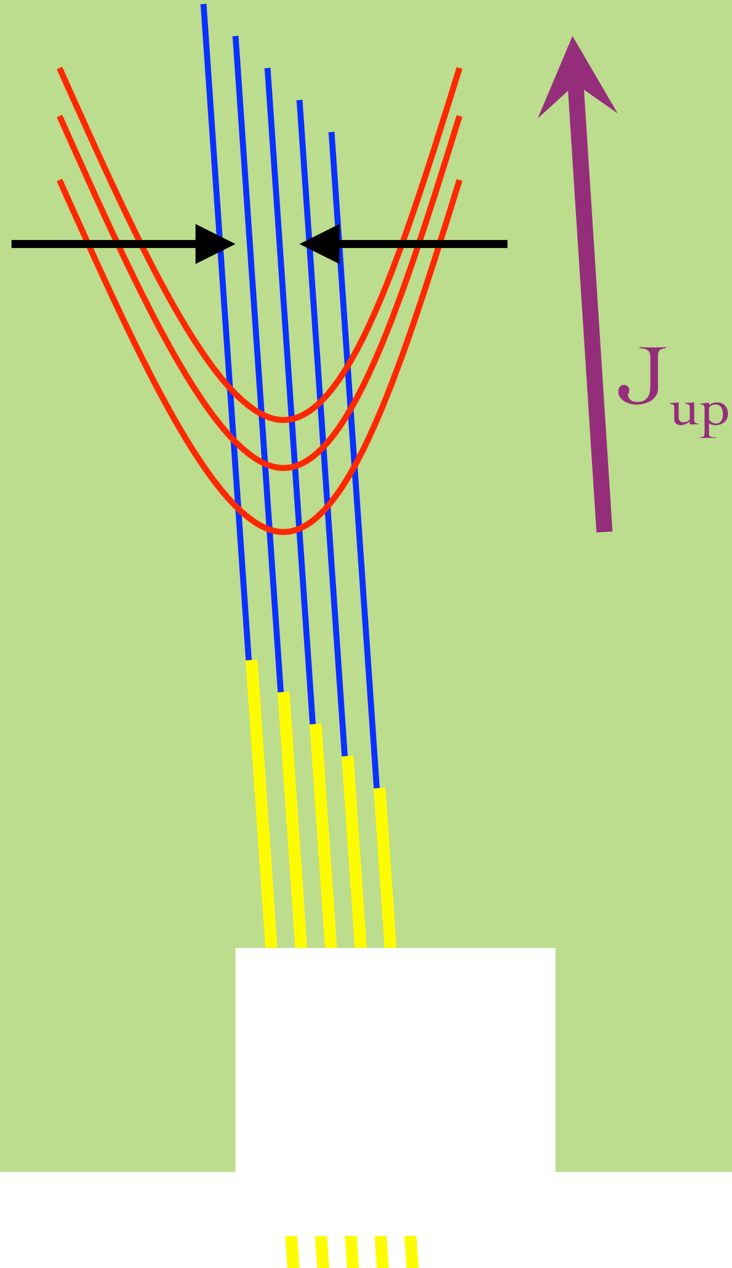
Auroral ionosphere primer

- Currents up
- Currents down
- Structure in time
- Structure in space

Green and Black Aurora Over Norway
Credit & Copyright:
Frank Andreassen
from the "Astronomy Picture of the Day"

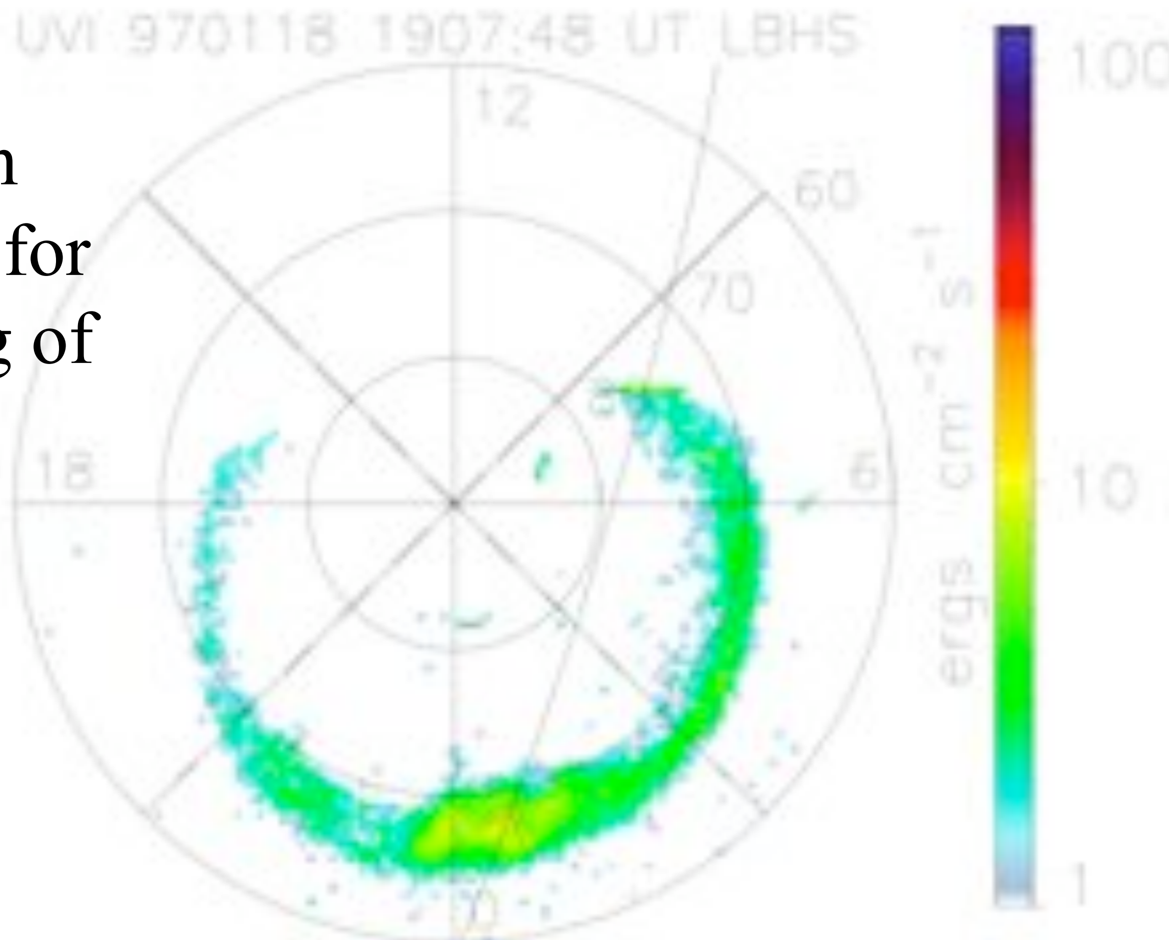
Simplest aurora picture

- External current requirement
- Convergent E-perp
- Closed potentials
- Electrons down
- UPward current
- Enhanced Pedersen conductivity
- Quasistatic (10s s)
- Large-scale (10s km)



Simplest aurora picture

- Simple precipitation picture can be used for large-scale mapping of static structures



Simplest aurora picture

- and for zeroth-order understanding of smaller structures.
- until they start to move…

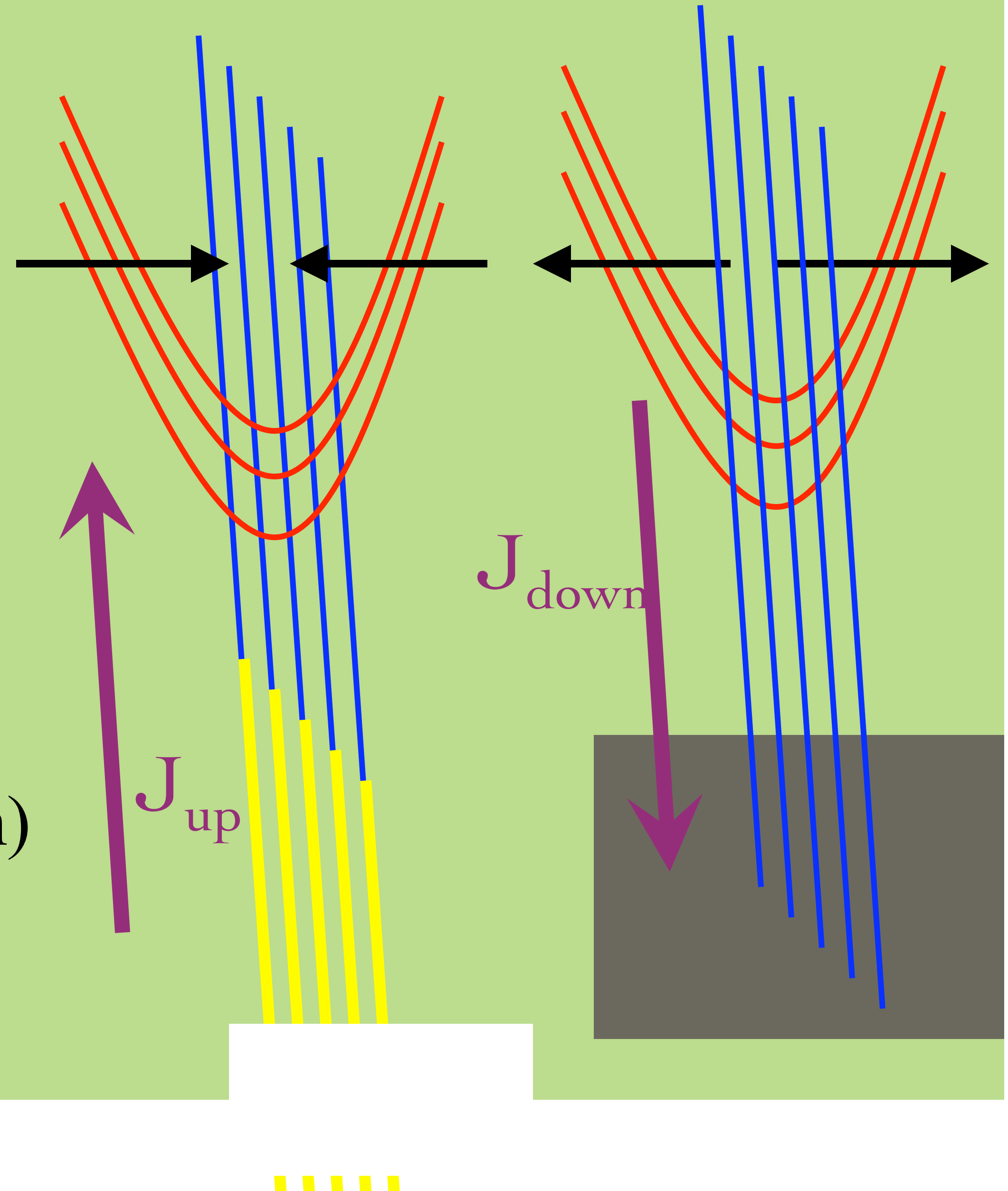
Jan Curtis


Auroral currents

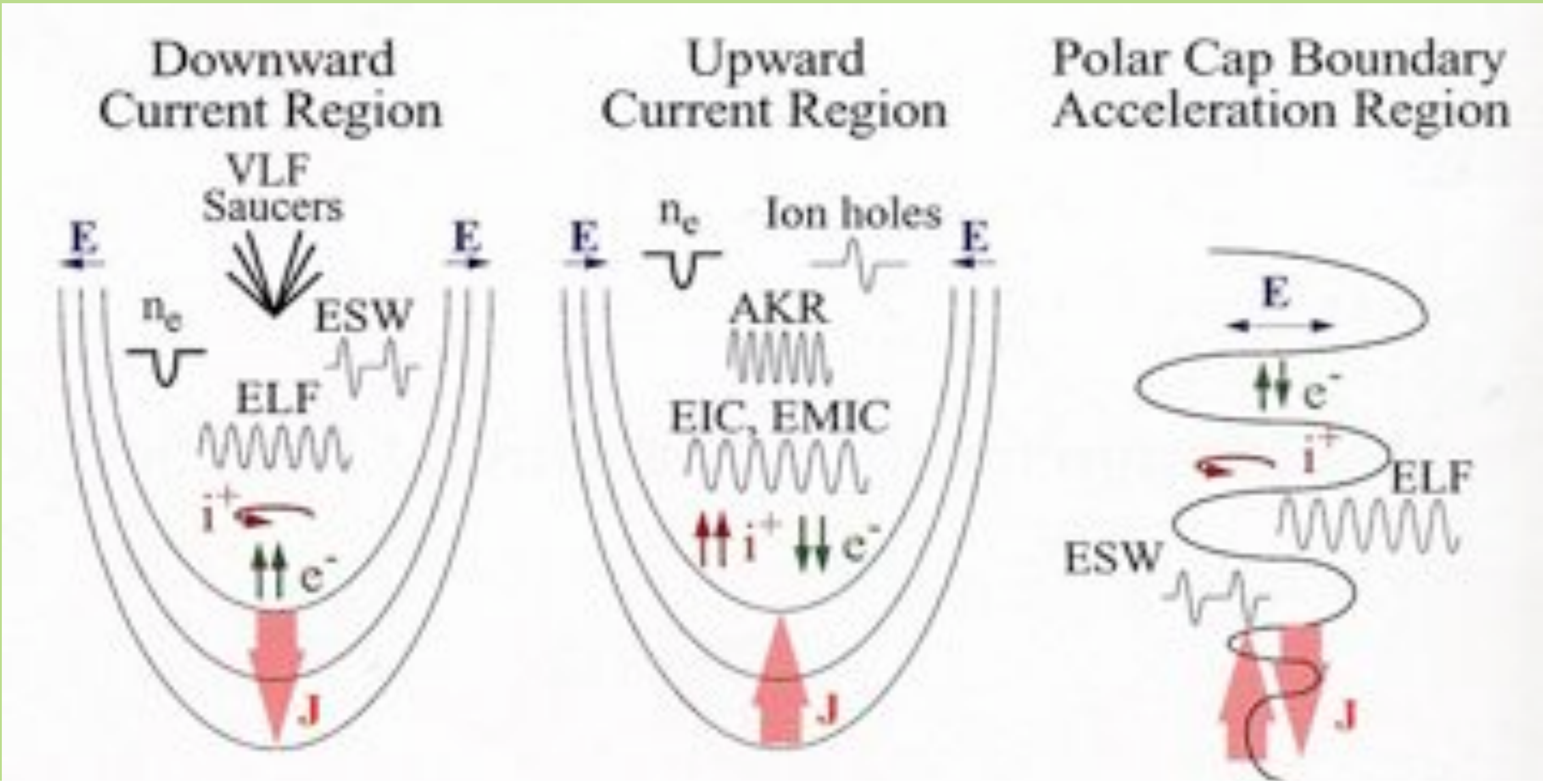
- A more complete auroral system picture builds on the idea of field aligned current systems.
- Next we consider downward-current-region aurora
- “Black” or “dark” aurora

Aurora up and down

- DOWNward current
- Electrons up
- Depleted ionospheric density
- Closed potentials
- Divergent E-perp
- Quasistatic (1s s)
- Medium-scale (1s km)

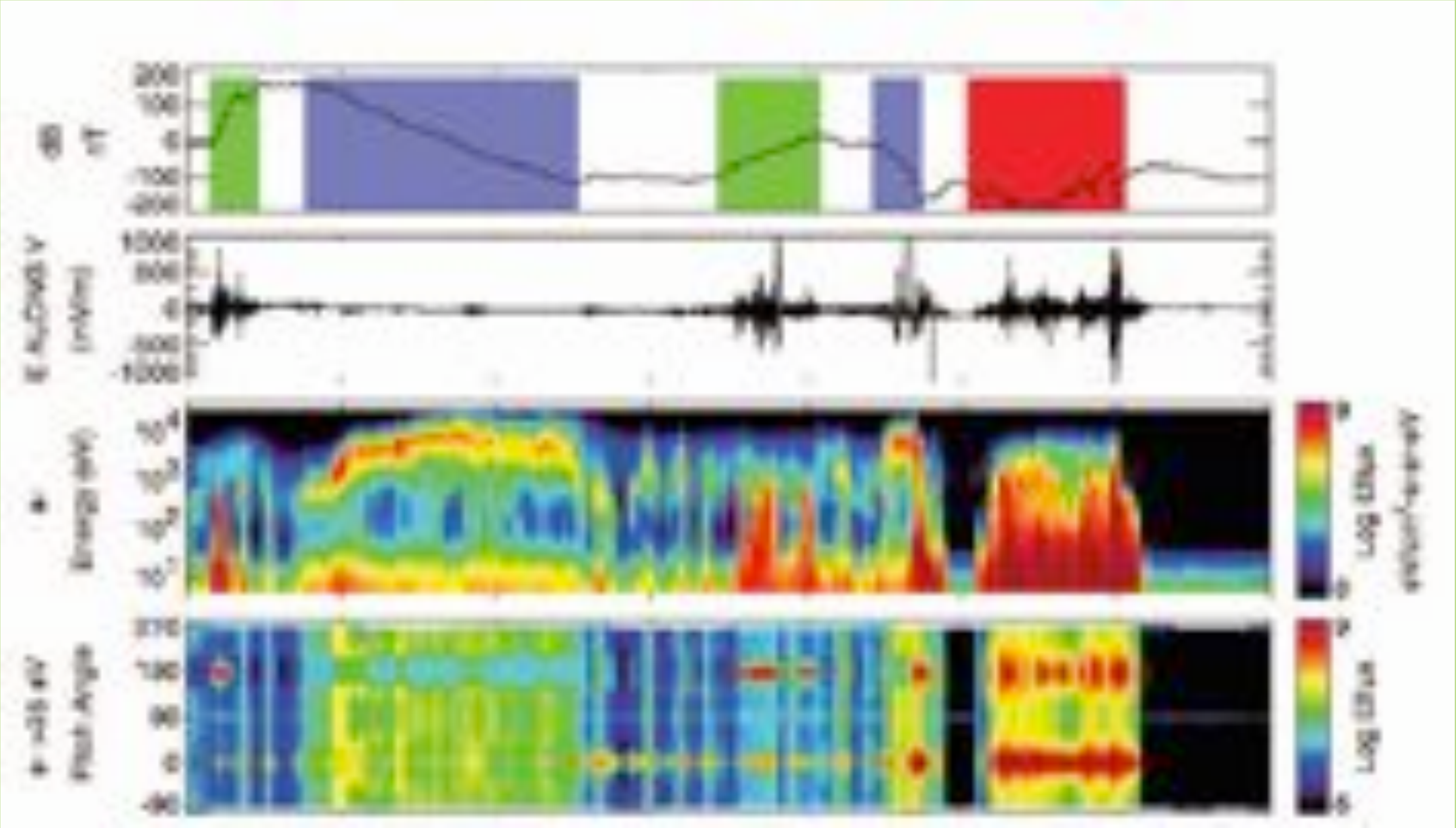


Aurora up, down and varying



Auroral Drivers

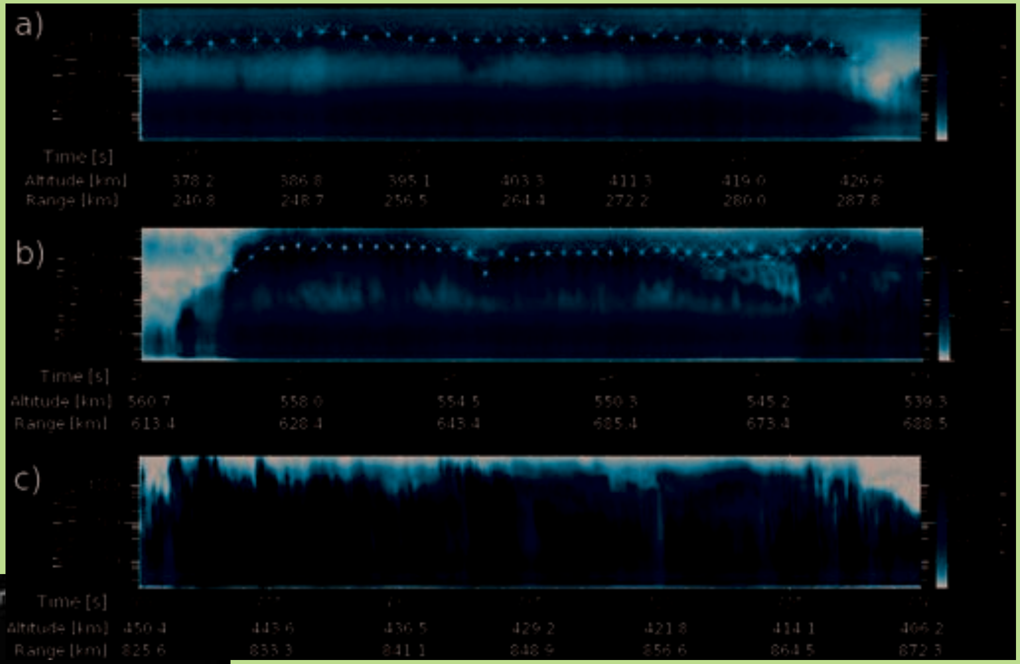
upward, downward, Alfvenic: each have distinct distribution functions

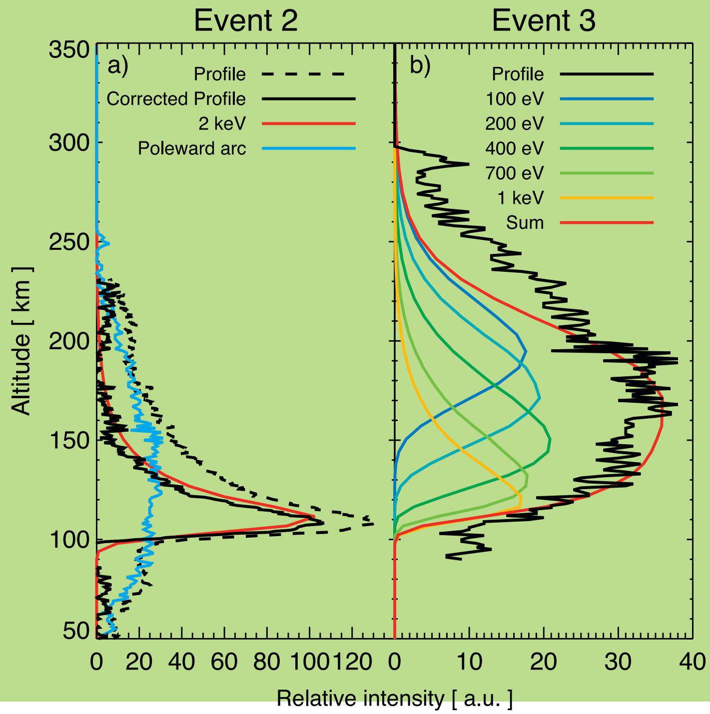


Paschmann, 2002

Auroral Drivers

- Finer details: shape of the distribution function for source and acceleration mechanism





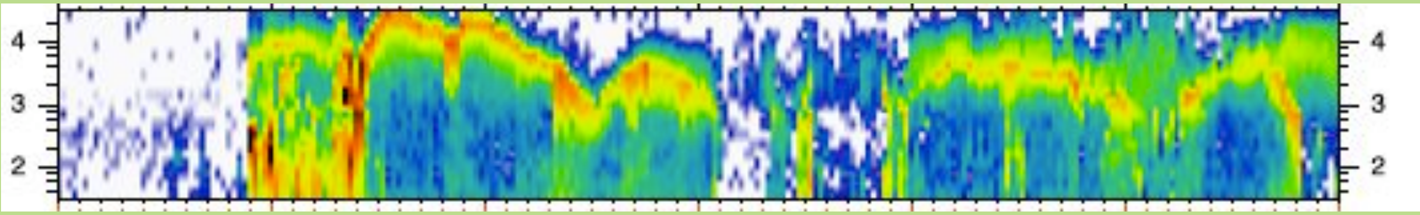
Mella, Hampton et al., JGR 2011

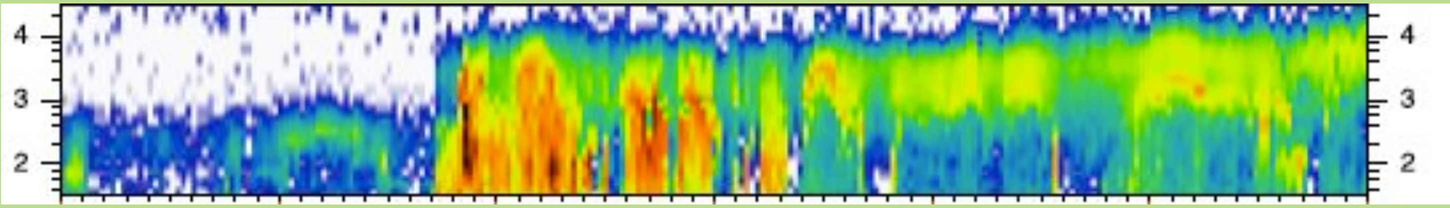
Auroral Drivers

- Much observational information: rockets, FAST, DMSP
- ISSI/Fast picture: upward, downward, Alfvenic
- Newell stats: energy input from accelerated, diffuse, broadband
- Finer details: shape of the distribution function for source and acceleration mechanism

Auroral Drivers

- Newell stats: energy input from accelerated, broadband, and diffuse (e- and ion)
- Empirical model based on DMSP

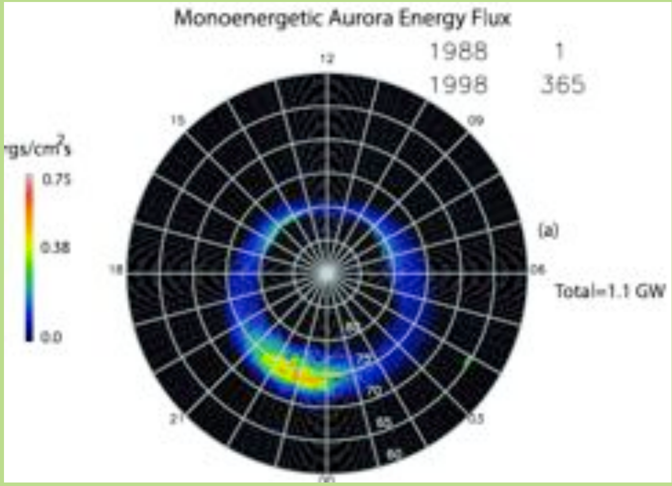


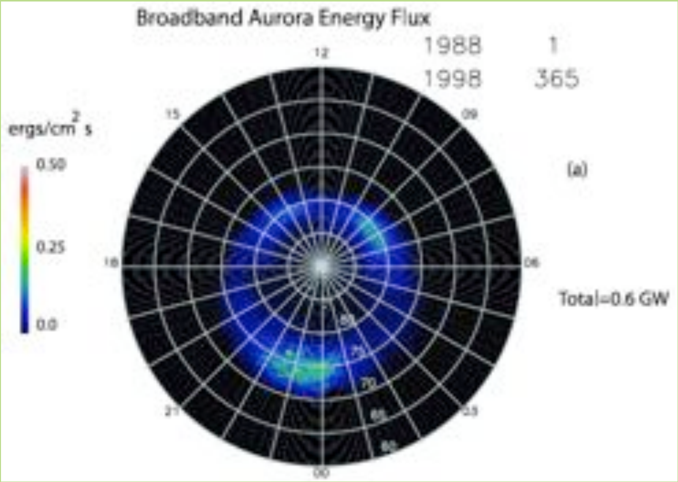


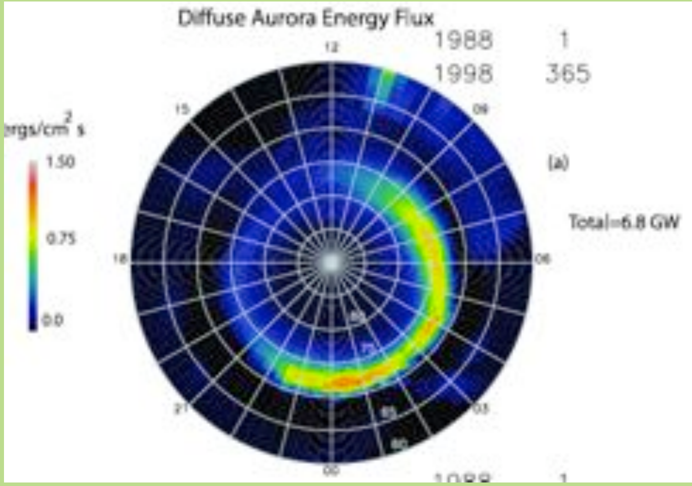
Newell, JGR, 2009

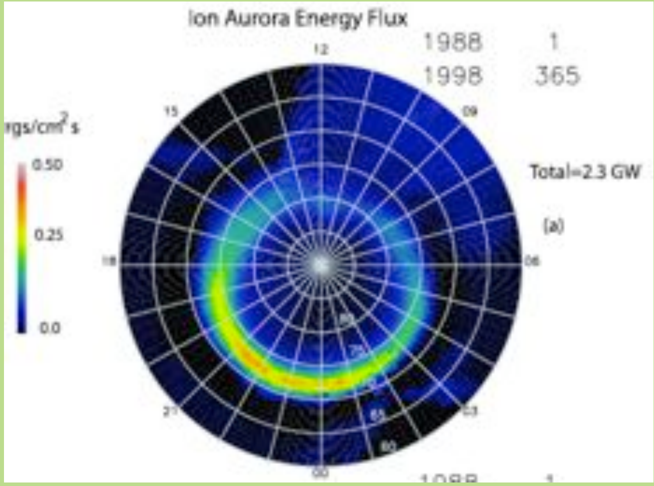
Auroral Drivers

- Interesting non-intuitive results about effects of 4 types of precipitation









Newell, JGR, 2009

Auroral Drivers

- Diffuse aurora 71-84% of energy flux (*"the least glamorous and arguably least studied form of auroral precipitation is the most energetically important"*)
- Monoenergetic more energy flux (10-15%) than BB (6-13%)
- BB rises fastest with activity, and can be highest number flux, especially of soft electrons; highest energy flux below 1 keV
- So ionospheric heating and outflow significantly affected by BB

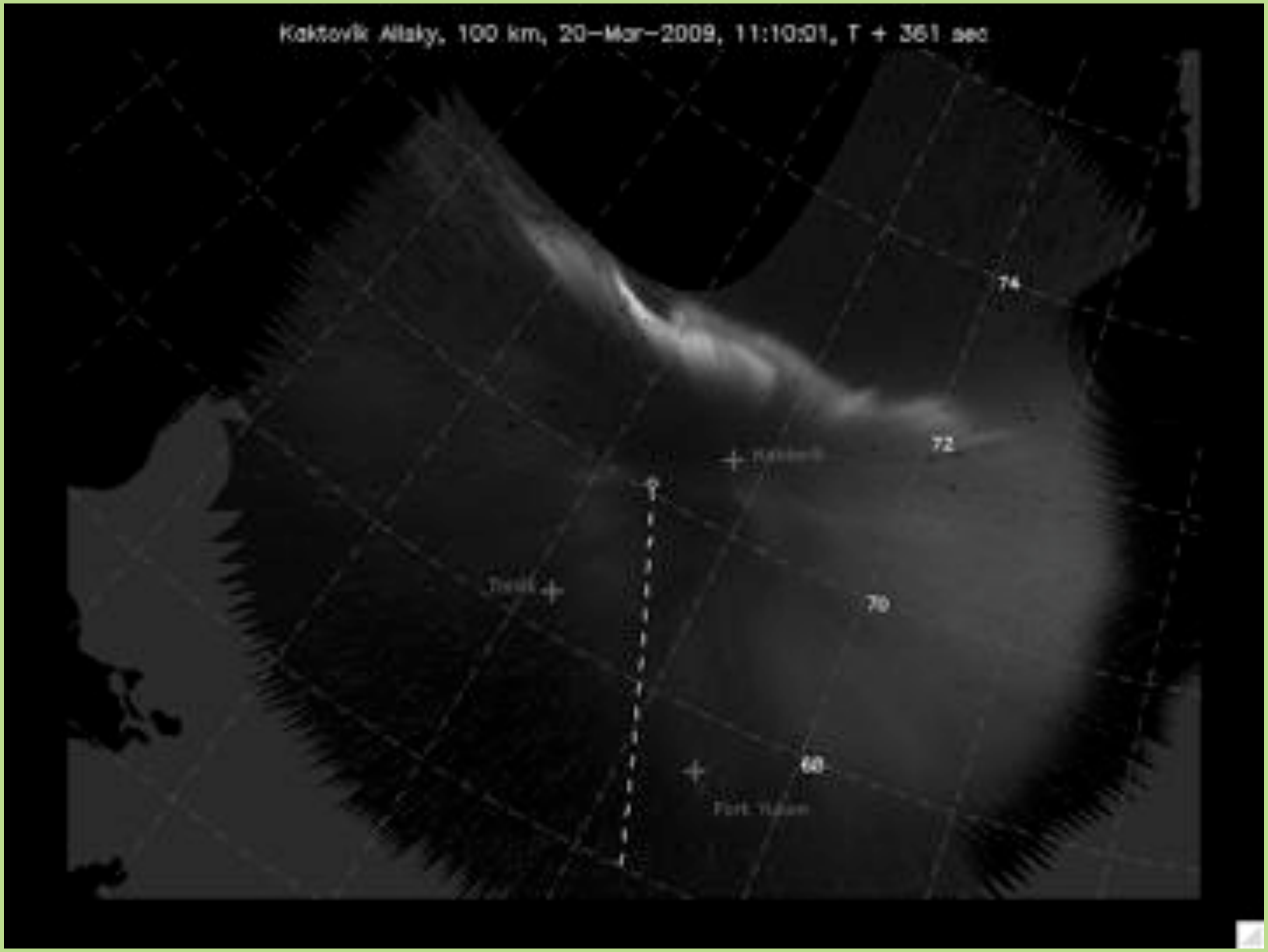
Newell, JGR, 2009

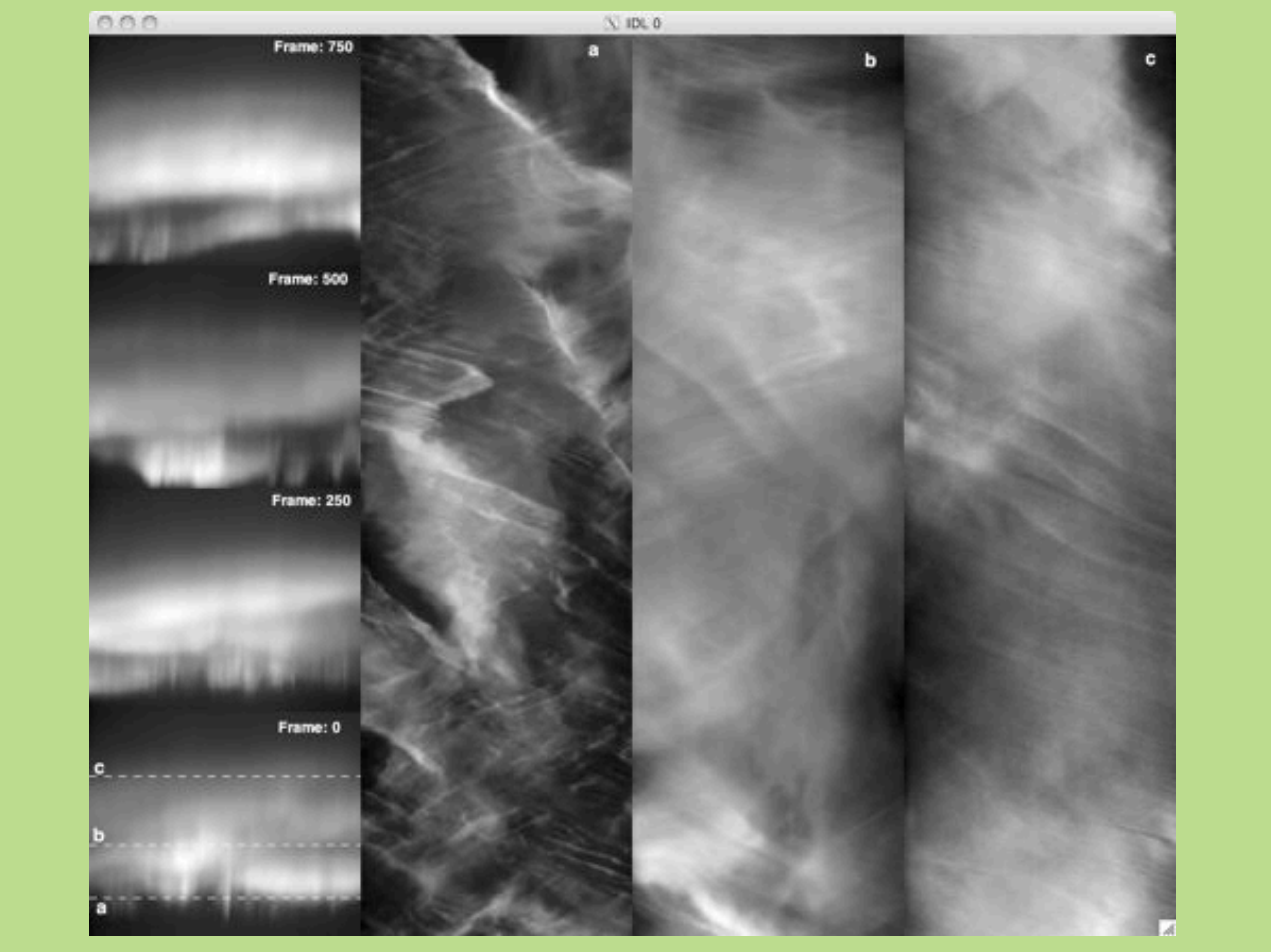
e pur si muove

(but it does move!)

galileo galilei

Different arcs move differently

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c
b
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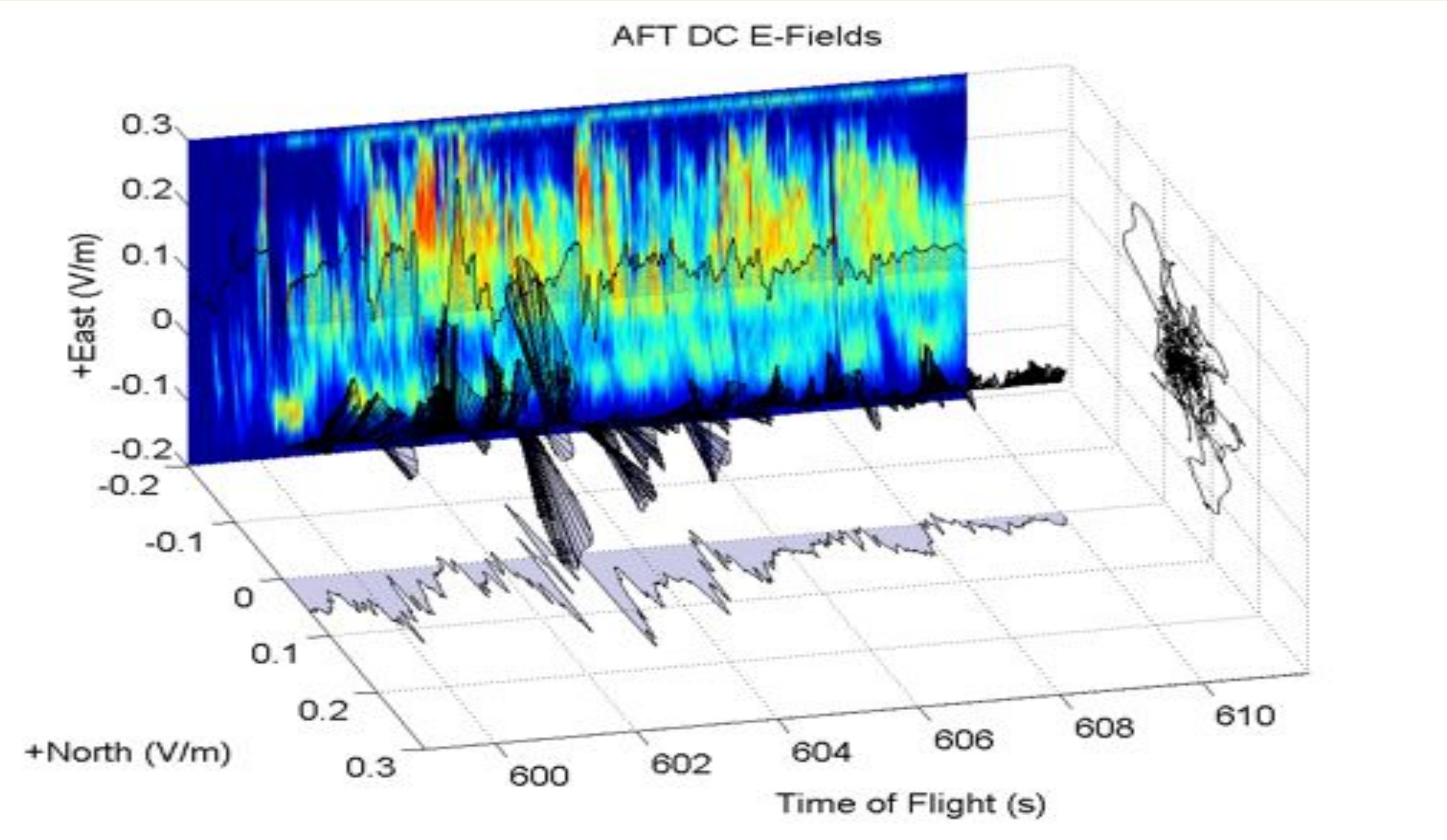
Tall rays: Alfvenic δ**E** and δ**B**



(note: δE lags e- precipitation, parallel phase velocity)

What would it take…

To separate d/dx from d/dt

To measure shears

To quantify the changing aurora?

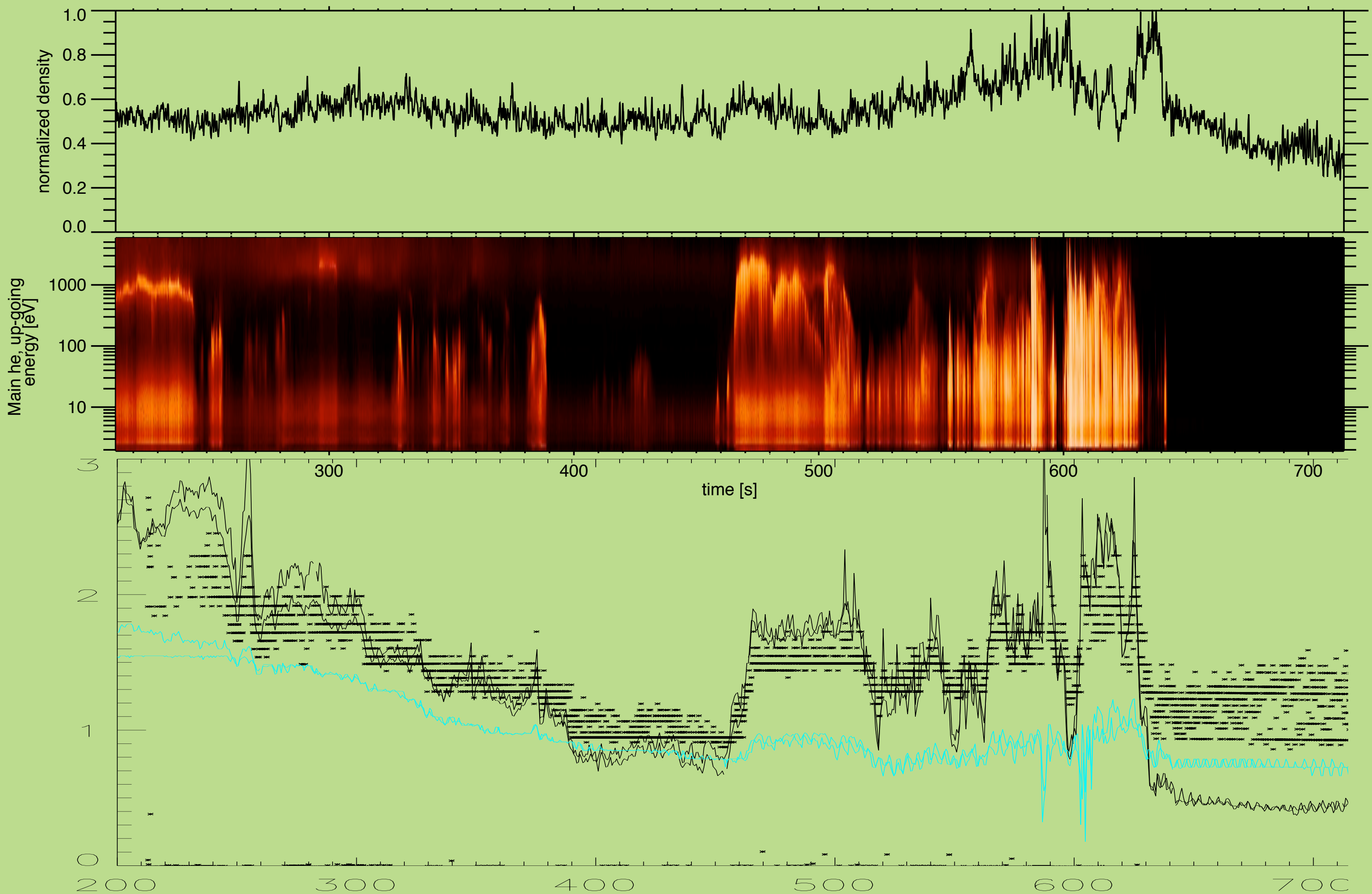
Given this motion and structure

What controls it?

Magnetospheric driver?

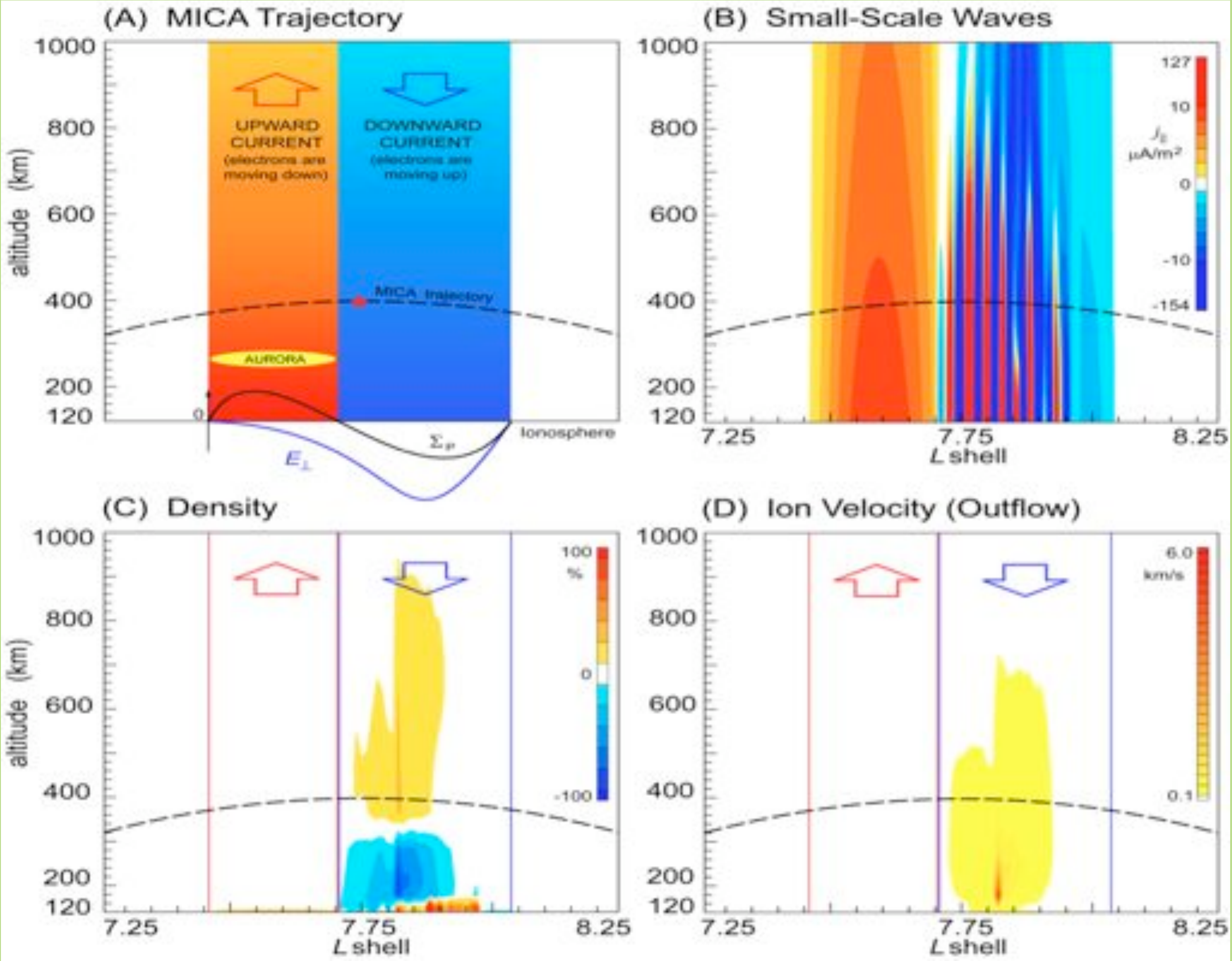
Ionospheric control? ..some examples:

n_i, J_e, ϕ_{sc}



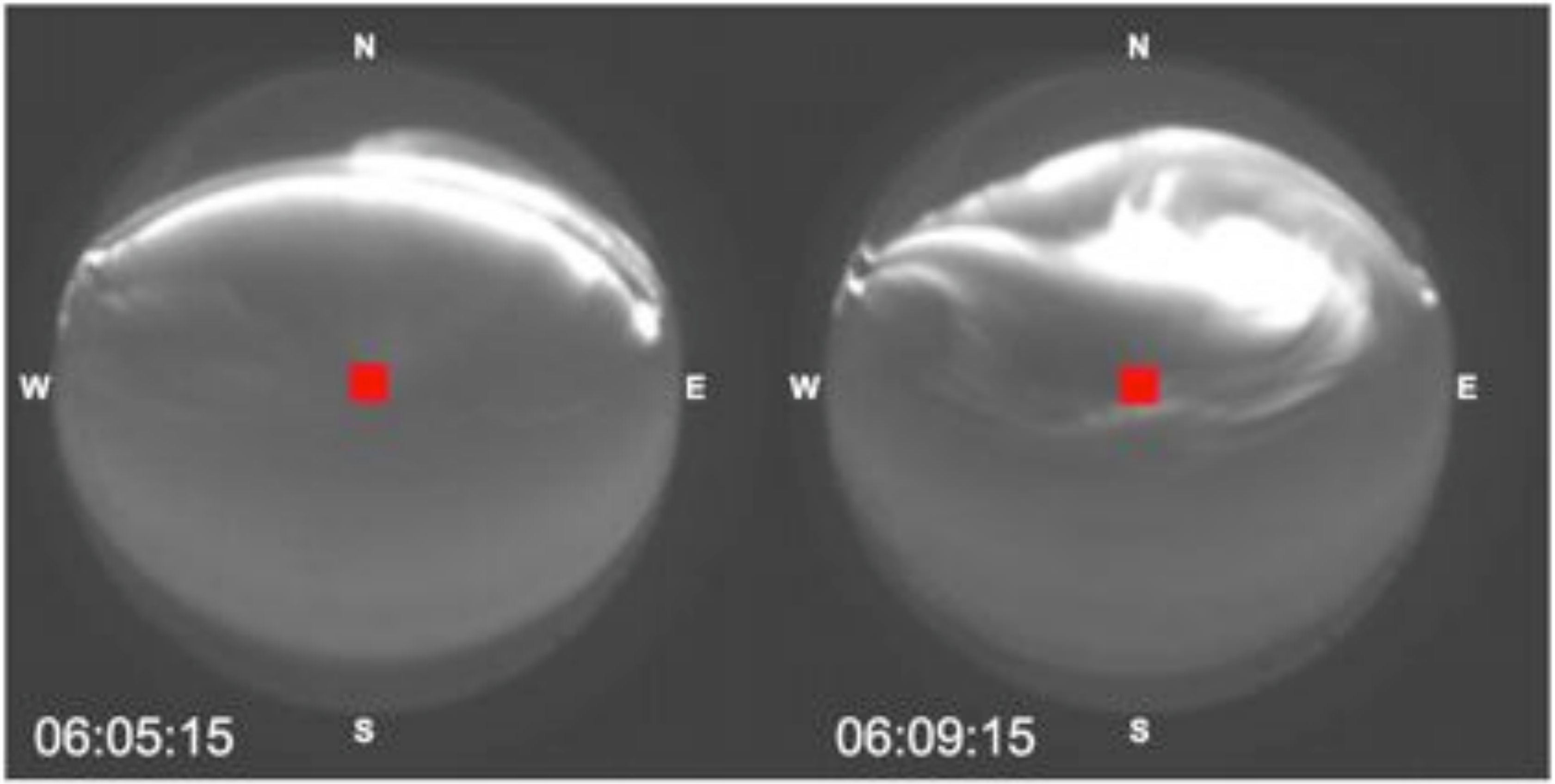
normalized density
1.0
0.8
0.6
0.4
0.2
0.0
Main he, up-going
energy [eV]
1000
100
10
300
400
500
600
700
time [s]
3
2
1
0
200
300
400
500
600
70C

MICA rocket: study of ionospheric modulation by dark aurora



Model: Anatoly Streltsov, Dartmouth

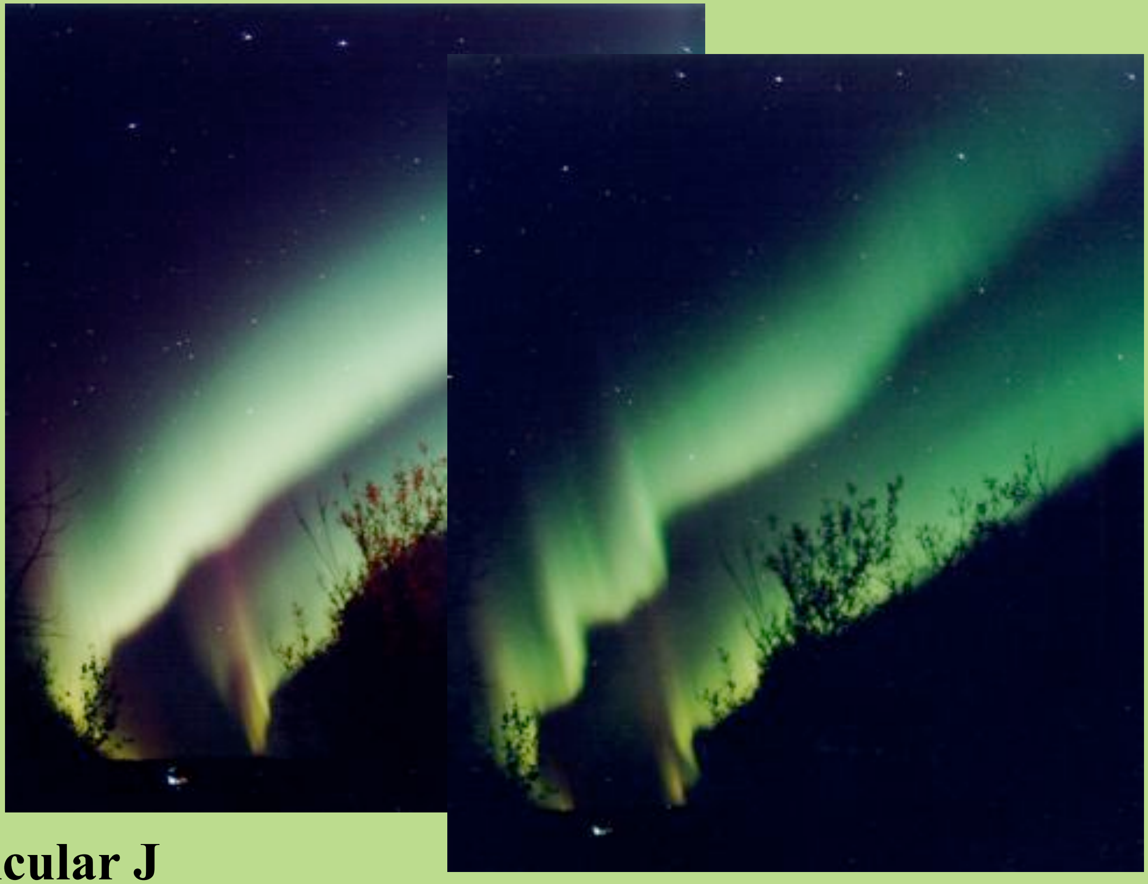
H(f)AARP: modification of ionospheric conductivity



$$\nabla \cdot (\Sigma_P \mathbf{E}_\perp) = -j_\parallel$$

Streltsov et al., JGR, 2010; GRL 2010

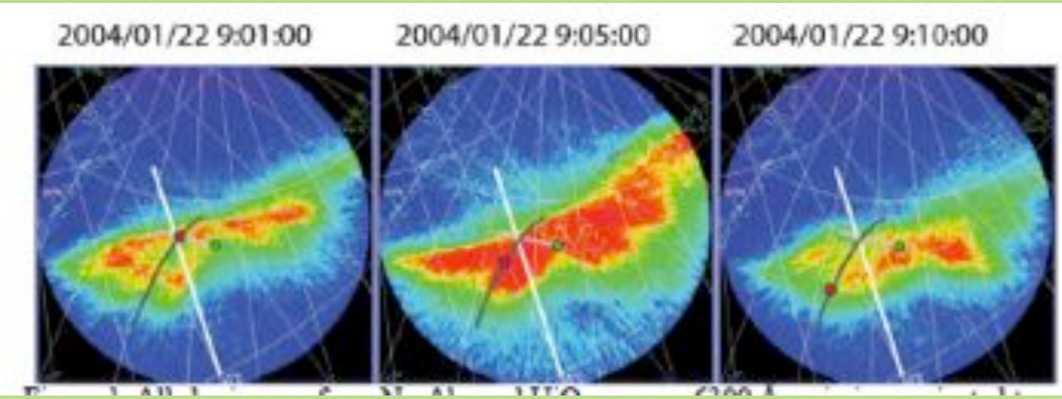
Outline



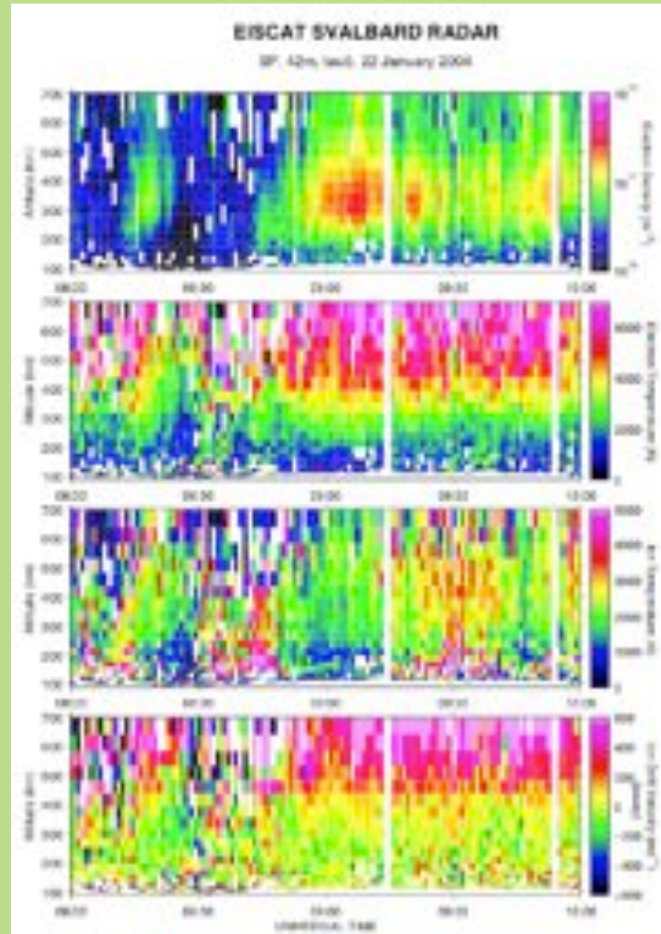
Jan Curtis

- Aurora
- ***Ionosphere***
  - **Structure, composition**
  - **Altitude profiles**
  - **Hall and Pedersen**
  - **Collisions and perpendicular J**
  - **Response questions**
- Plasma
- Processes
- Instrumentation and measurements
- Swarms

Altitude profiles of these interactions



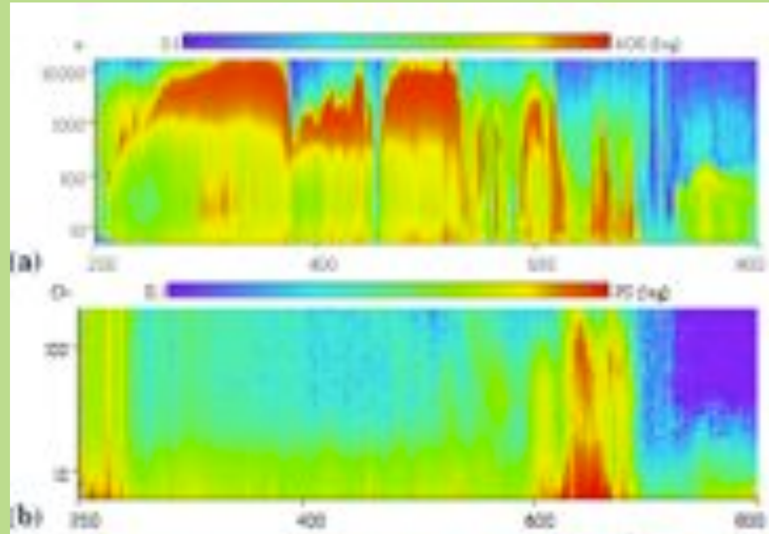
- Radar shows the plasma profiles
- Cameras show the input drivers
- Lidar to see the neutrals…

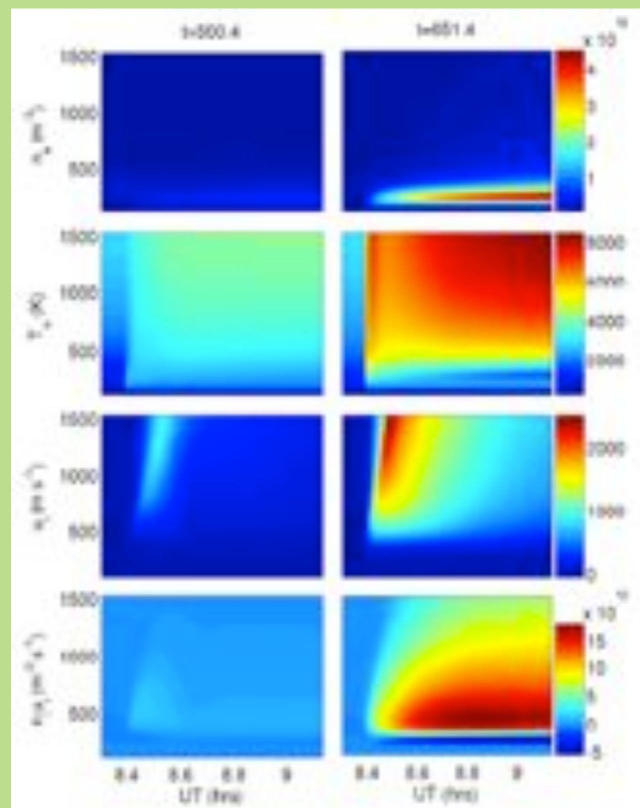


Frederick-Frost, JGR, 2007

Ionosphere-thermosphere response to auroral drivers

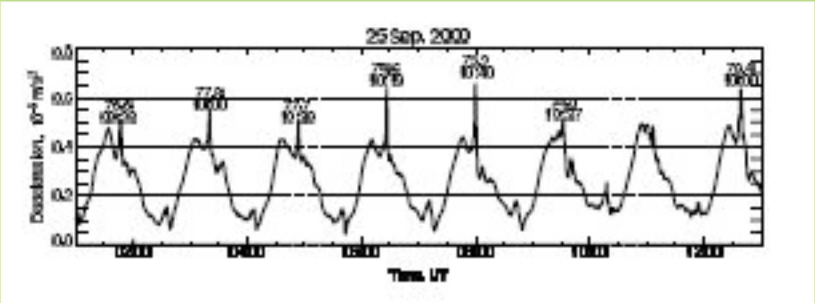
- Conductance from precipitation, empirical *(Reiff, 1984)*
- Downward current region ionospheric electron evacuation *(Marklund, 2001)*
- Transport models for inversions of camera profiles *(Lummerzheim, Transcar)*





Lynch, Zettergren, AnnGeo, 2007

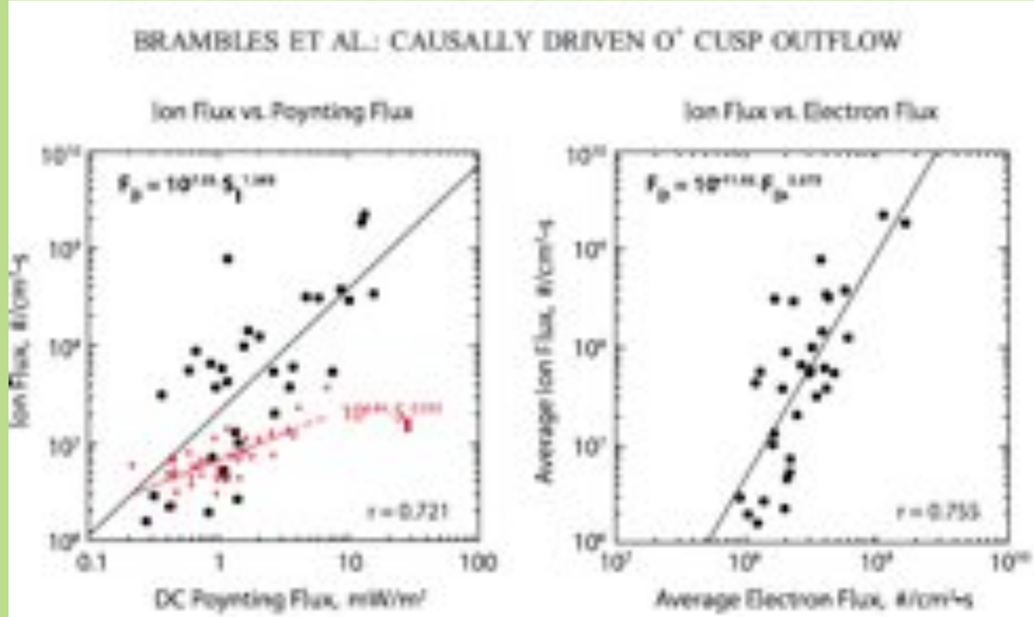
Ionosphere-thermosphere response to auroral drivers



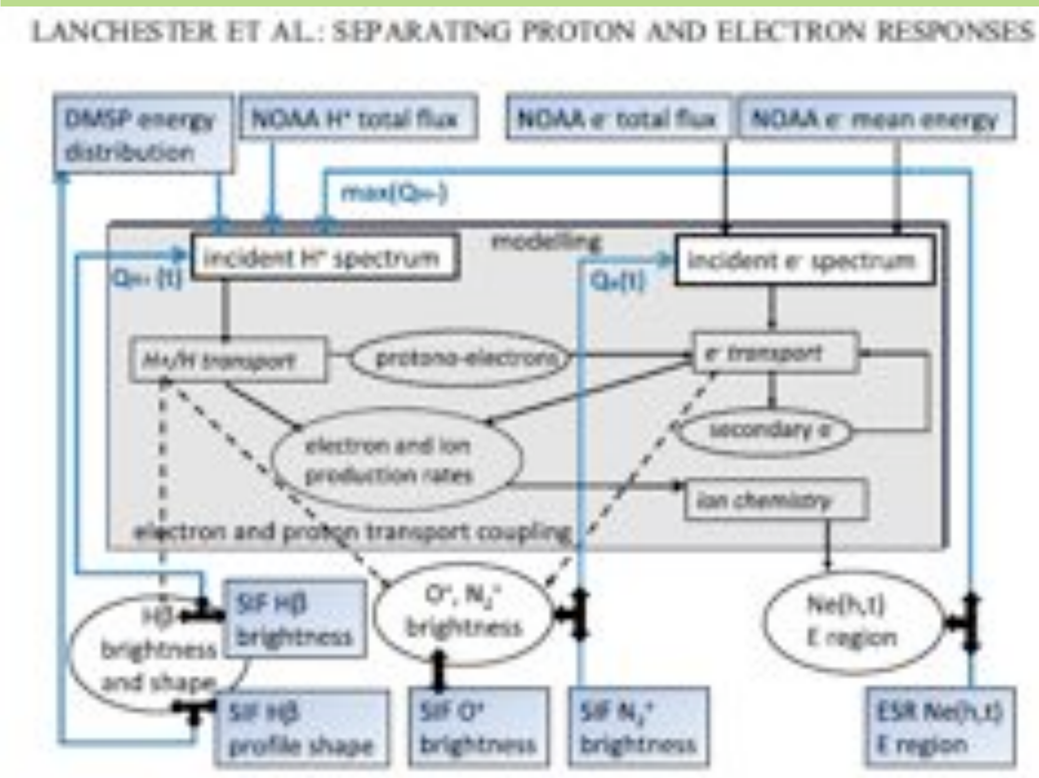
- Neutral upwelling and ion outflow
- CHAMP *(Luhr 2004), RENU s* studies of cusp upwelling: accelerometer signatures in cusp
- Difficult in-situ measurement: high voltages at low altitudes
- Drag studies
- Chipsats

Ionosphere-thermosphere response to auroral drivers

- Empirical studies of “in” vs “out”
- Detailing the actual interactions



Brambles, 2010, JGR



Lanchester, 2011, JGR

Ionosphere-thermosphere response to auroral drivers

- Can we quantify this?
- Rocket observations turning to study of effects rather than drivers

Movie by Mark Conde, UAF/GI

MICA rocket, FPI, PFISR, ASC

Outline

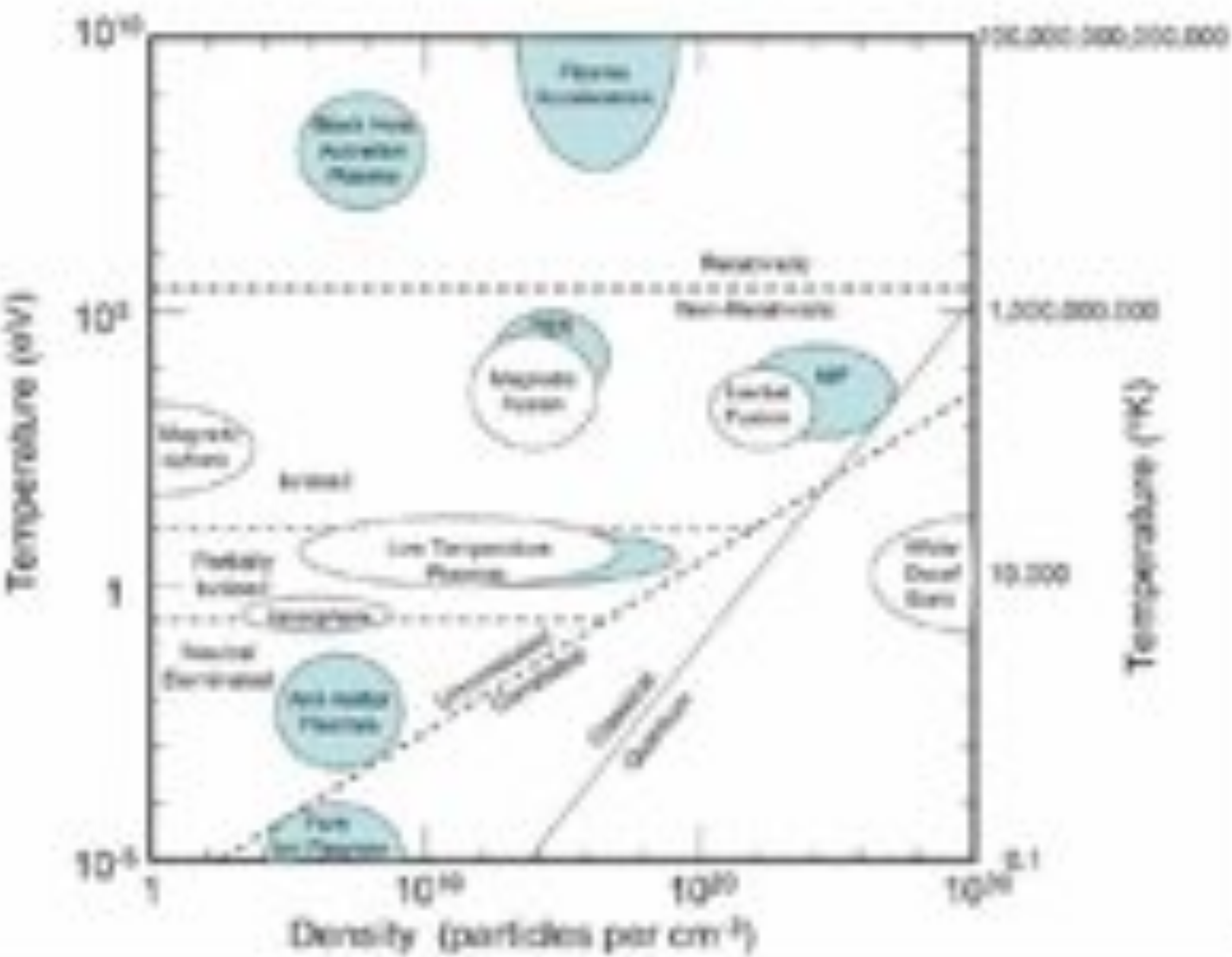
Jan Curtis

- Aurora
- Ionosphere
- ***Plasma***
  - **Characteristics of ionospheric plasma**
  - **Sheaths and float potentials**
  - **Thick sheaths and floating instruments**
- Processes
- Instrumentation and measurements
- Swarms

Low Temperature Plasmas

$$\lambda_D = (\varepsilon_0 T_e / e^2 n_e)^{1/2}$$

$\lambda_D \sim L$	sheaths
$v_{Thi} \sim v_{system}$	wakes
$n_e \sim n_{neutral}$	collisions


Temperature (eV)
Temperature (°K)
Density (particles per cm⁻³)
1
10,000

"Typically" Studied Plasmas

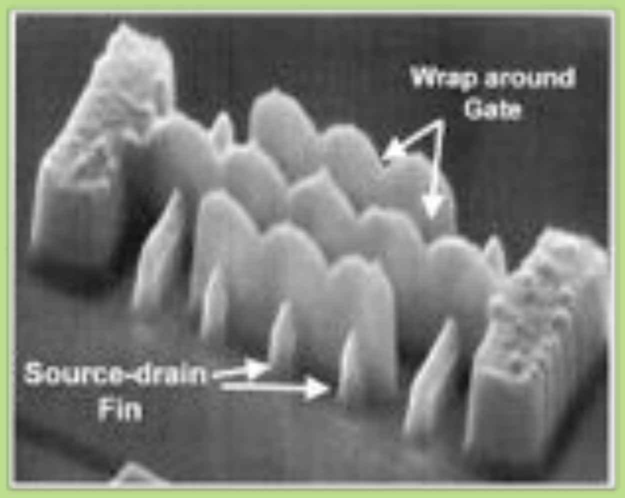
Lab experiments: fusion applications

Reconnection modelling: no solid surfaces

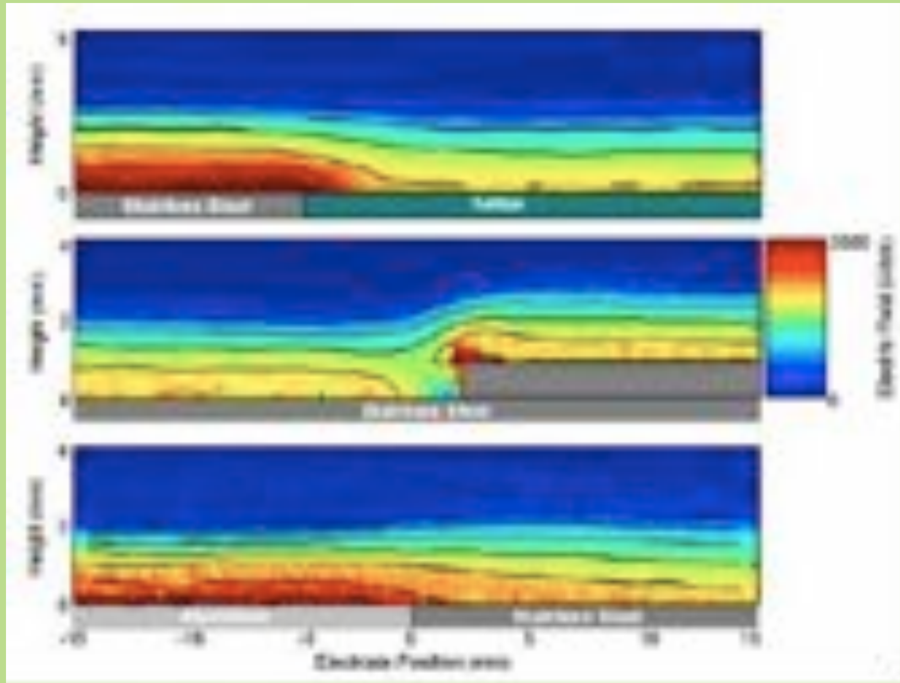
MHD and PIC codes: rarely consider λ_D
dominated rgions

Low Temperature Plasmas

From NRC Plasma 2010 study:



Future designs for microelectronics devices require fabrication of intricate structures such as this trigate transistor fabricated in silicon having dimensions of only tens of nanometers.
Source: M. Mayberry, Intel Corp

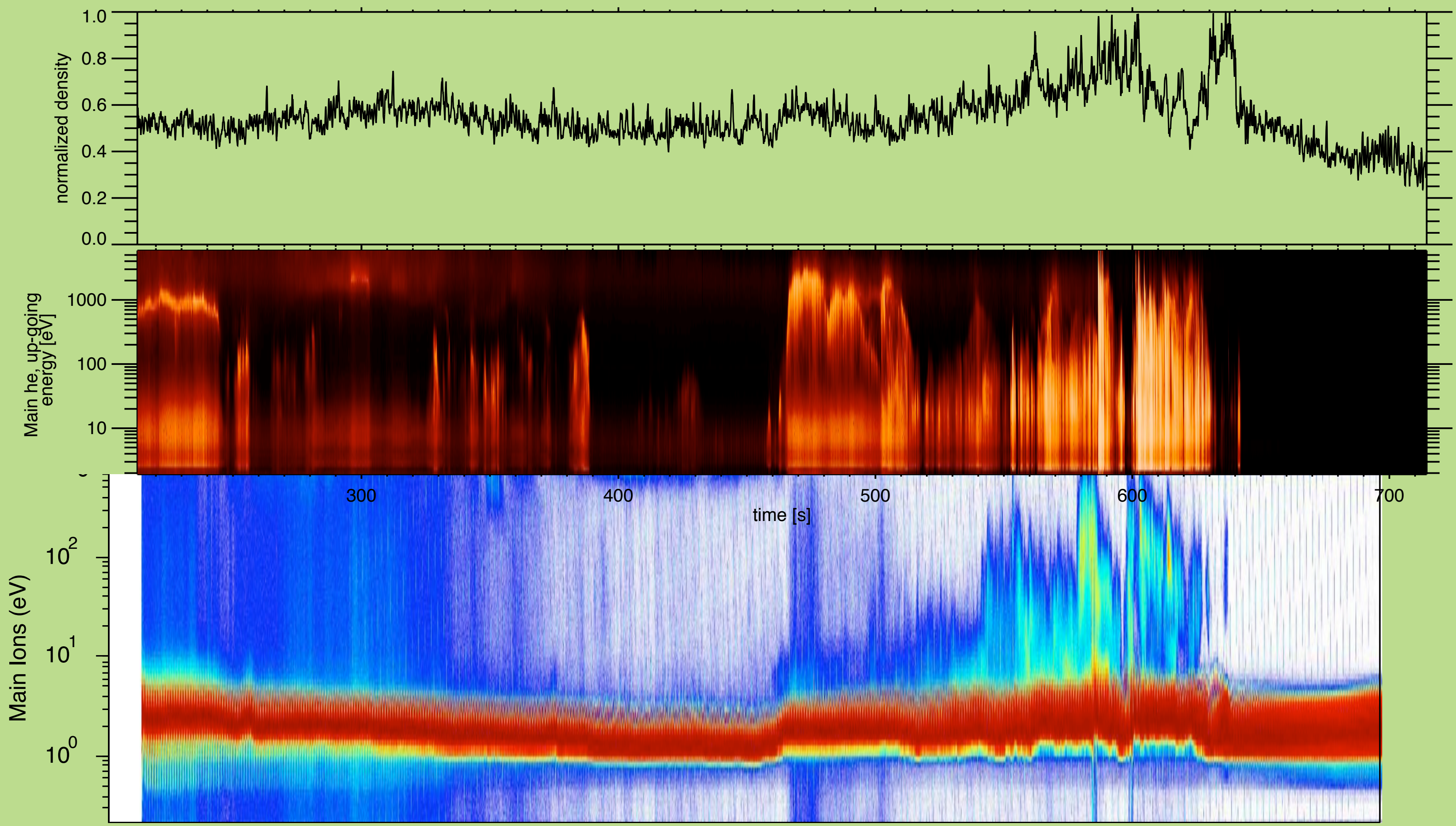


Non-invasive diagnostics provide insights to complex phenomena occurring in plasmas. Here electric fields above the electrodes of a semiconductor processing plasma are measured using laser-induced fluorescence.

Low Temperature Plasmas

Planetary formation and rings
Medical physics
Industrial plasmas
Dusty plasmas
Ionospheric plasmas

Threaded by common theme of interactions with neutrals and surfaces



normalized density
1.0
0.8
0.6
0.4
0.2
0.0
Main he, up-going energy [eV]
1000
100
10
300
400
500
600
700
time [s]
Main Ions (eV)
10^2
10^1
10^0

Sheaths and charging

- Cold, dark ionosphere: payload potential from current balance of thermal fluxes:

$$\Phi_{sc} = \text{“few” } kT_e$$

$$\text{“few”} = \ln(\mathrm{sqrt}(m_i/m_e))$$

- Since

$$je(\Phi_{sc}) + ji(\Phi_{sc}) = 0$$

$$n_e\, v_{the} \exp(e\Phi_{sc}/kT_e) - n_i\, v_{thi} = 0 \qquad (\text{or } v_{bohm} \text{ or } v_{ram})$$

- And, auroral precipitation can enhance Φ_{sc} by contributing to electron current collection

- Typically 2-4 V negative where T_e, $T_i < 1\text{eV}$; a significant perturbation to the observation

Sheaths and charging

- How then to measure the thermal plasma density?
- Not with the electrons
  - Even a positive probe can be surrounded by a negative payload sheath (MacDonald, JGR 2006; Frederick-Frost, PoP 2007)
  - This effect may be mitigated by photoelectron emission but not in lower dark ionosphere
  - T_e easier (Frederick-Frost, JGR 2007)
- Moen MNP: density in the sheath (Jacobsen IOP 2010)
- Sheath problems:
  - Perturbations (Montgomery); Wakes (Hutchinson)
- Thermal ions? Core, but sheath effects
- RPA nicely low-resource: no high voltage!
- *Where put steps on I-V curve if ϕ_{sc} dominant and varying?*

Charging models: complications

Photoemission: charge positive, density
dependent

Secondary emission: more positive or
more negative

Area ratios: how big is your biased probe?
how flat is your surface?

Upshot: hidden or poorly measured
populations

Ionospheric parameters

Dark ionospheric plasma: spacecraft charge a few kT_e negative:

$J_{tot} = -e\, n_e\, v_{the} \exp(-ephi/kT_e) + e\, n_i v_{thi} = 0$

Solve for e phi = $-kT_e \ln[v_{the}/v_{thi}] \sim$ few kT_e

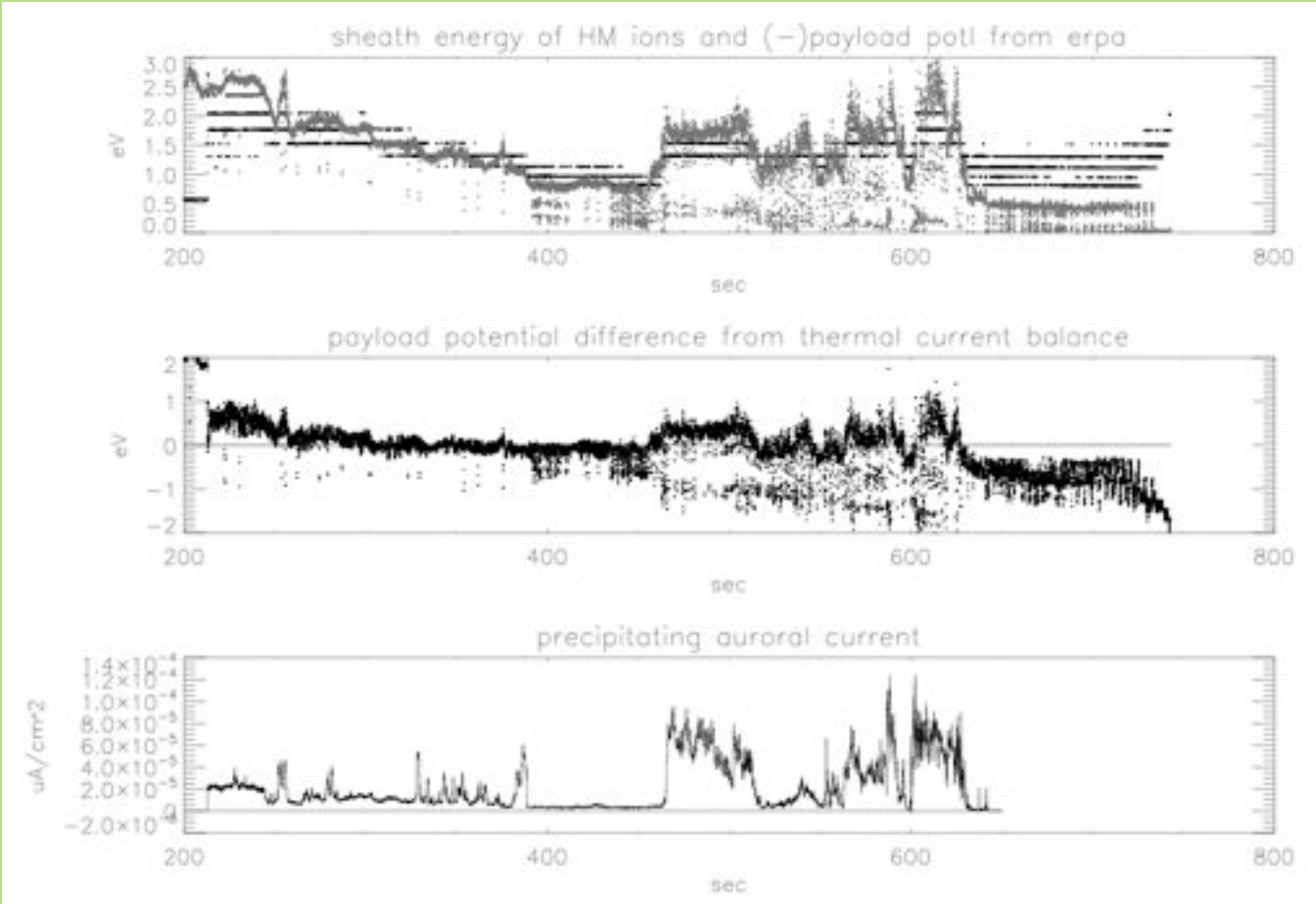
In sunlight or aurora, varies (-5V to +2V)

n_e a few 10^3 or 10^4/cc; λ_D a few to 10 cm

And another thing…Φ_{sc} in arcs

- Thermal ion measurements sensitive to Φ_{sc}
- Φ_{sc} sensitive to T_e ("5 kT_e")
- T_e strongly raised in soft precipitation
- Thermal current balance:
  - $J_{th}(e-) + J_{th}(ions) = 0$
- Thermal current balance plus auroral e-:
  - $J_{th}(e-) + J_{th}(ions) - J_{aur}(e-) + J_{secondary} = 0$
- $J_{secondary}$ dominates $J_{auroral}$, so less negative
- Φ_{sc} more negative in arc, but less than it would be from thermal current balance

Φ_{sc} in arcs on C2



…repeatable in the lab

Ionospheric thermal plasma facility

ELEPHANT

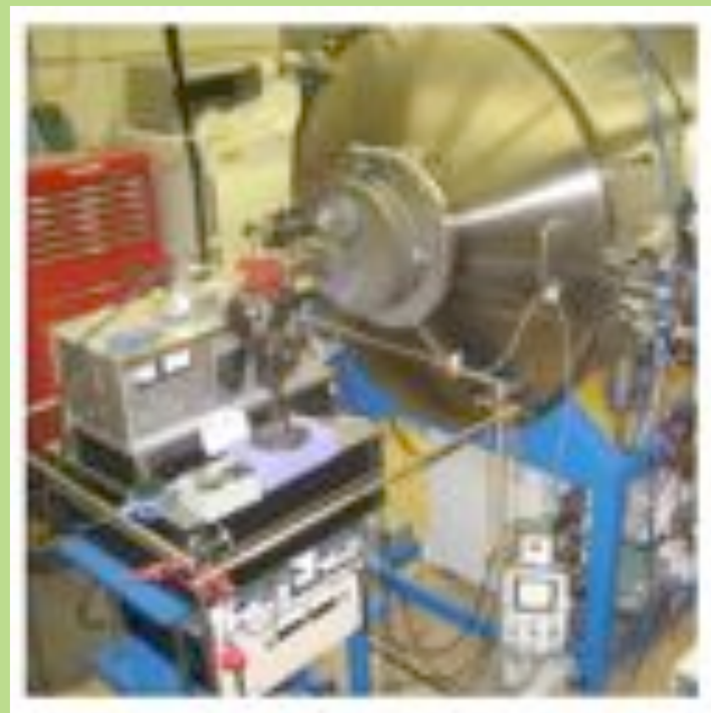
Experimental Low Energy Plasma for Hemispherical Analyzer Nominal Testing

Chamber Dimensions	1.2x1.5 m (14-400 λ_D)
Base Pressure	7e-8 Torr
Operational Pressure	9e-5 Torr
Ions unmagnetized	
Electrons magnetized	
Plasma Density	1e3-6e5 per cc
λ_D	0.3-8.4 cm
B	Earth Field

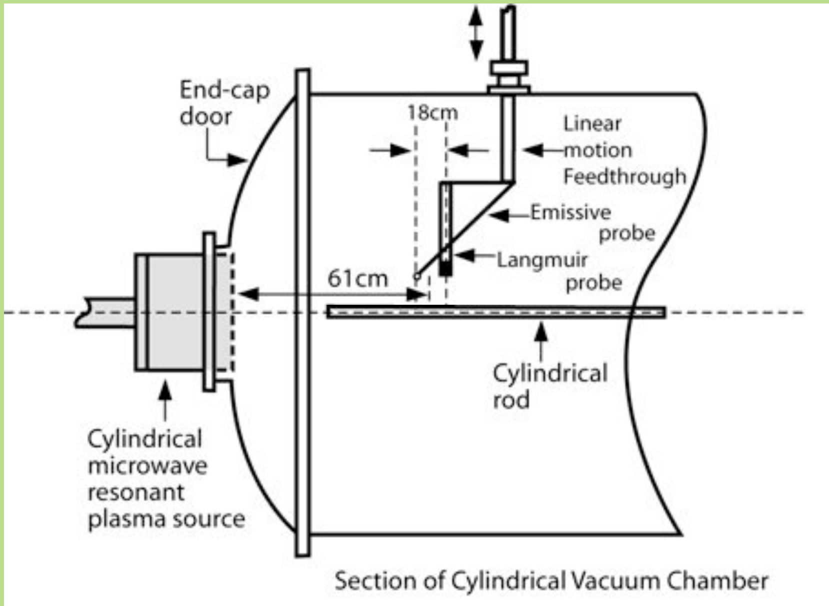
e-:	Ar+:
$T_e \sim 0.5$ eV	$T_i \sim 0.05$ eV
$V_{the} \sim 3e5$ m/s	$V_{thi} \sim 350$ m/s
$f_{ce} \sim 1e6$ Hz	$f_{ci} \sim 20$ Hz
$r_e \sim 0.05$ m	$r_i \sim 2.8$ m
$f_{pe} \sim 2.8e5\text{-}6.9e6$ Hz	$f_{pi} \sim 1e3\text{-}2.6e4$ Hz

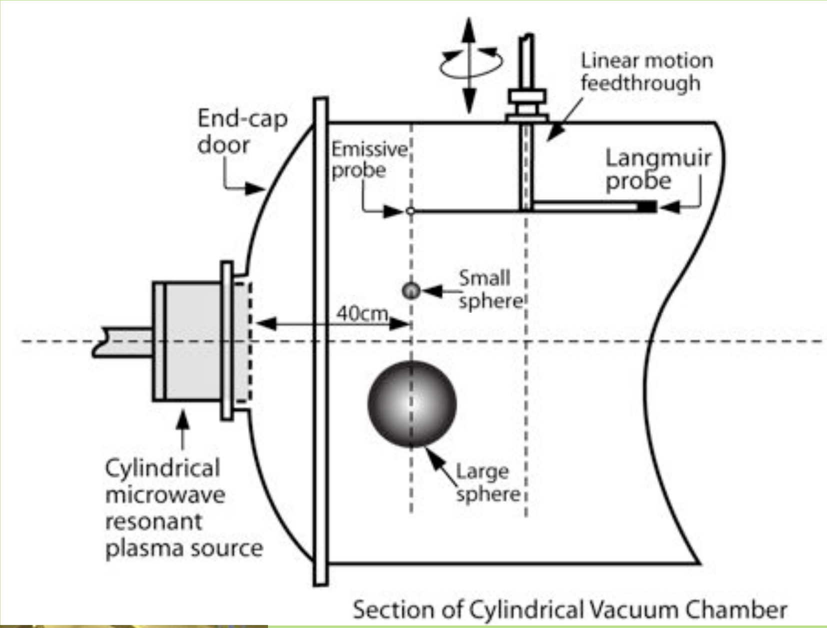
Collision frequencies:

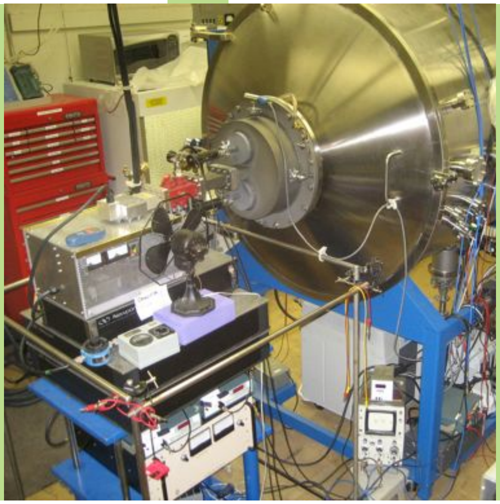
e-	Ar	Ar+
$\nu_{ee}<100$ Hz	$\nu_{eAr}\sim 3e5$ Hz	$\nu_{eAr+}<100$ Hz

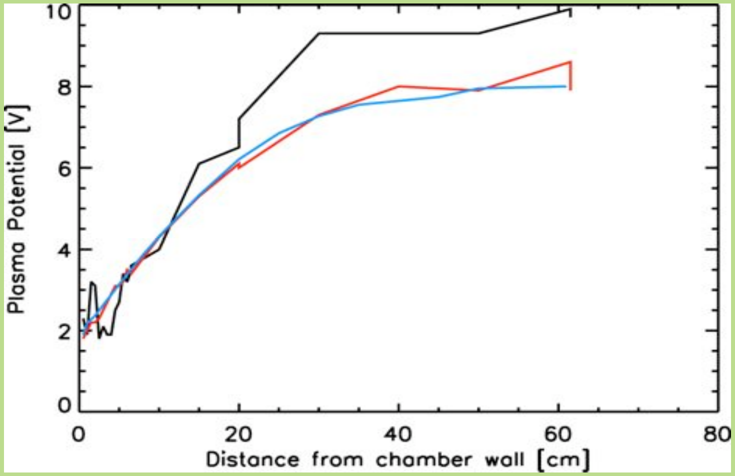


Facility and diagnostics

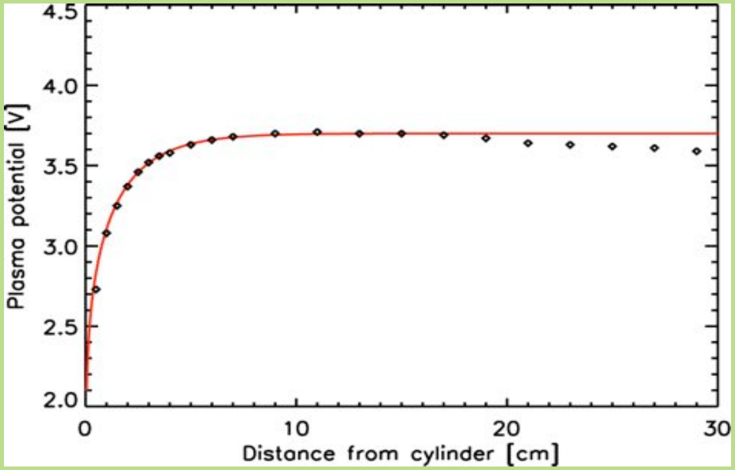








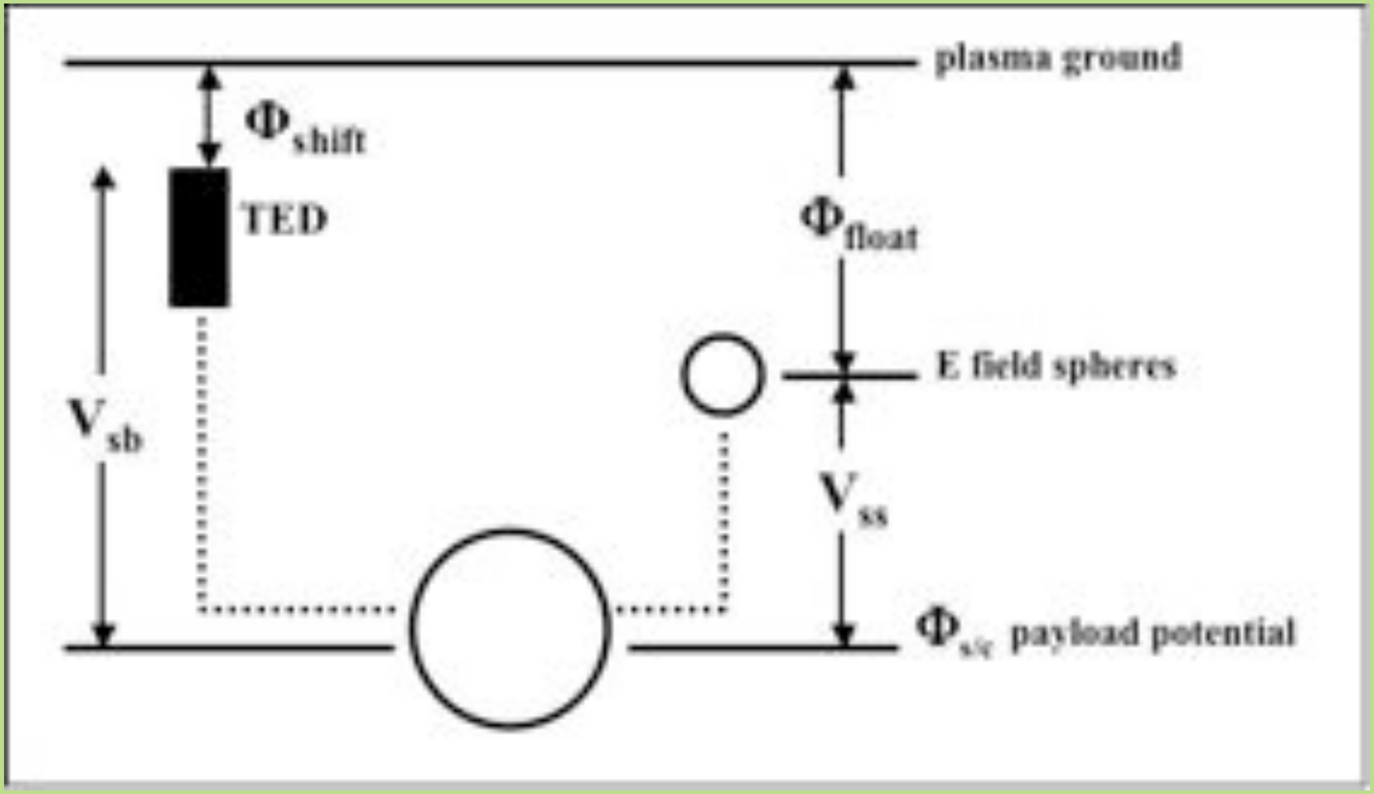
Sheath near chamber wall,
Using langmuir and emissive probes



Sheath near grounded cylinder

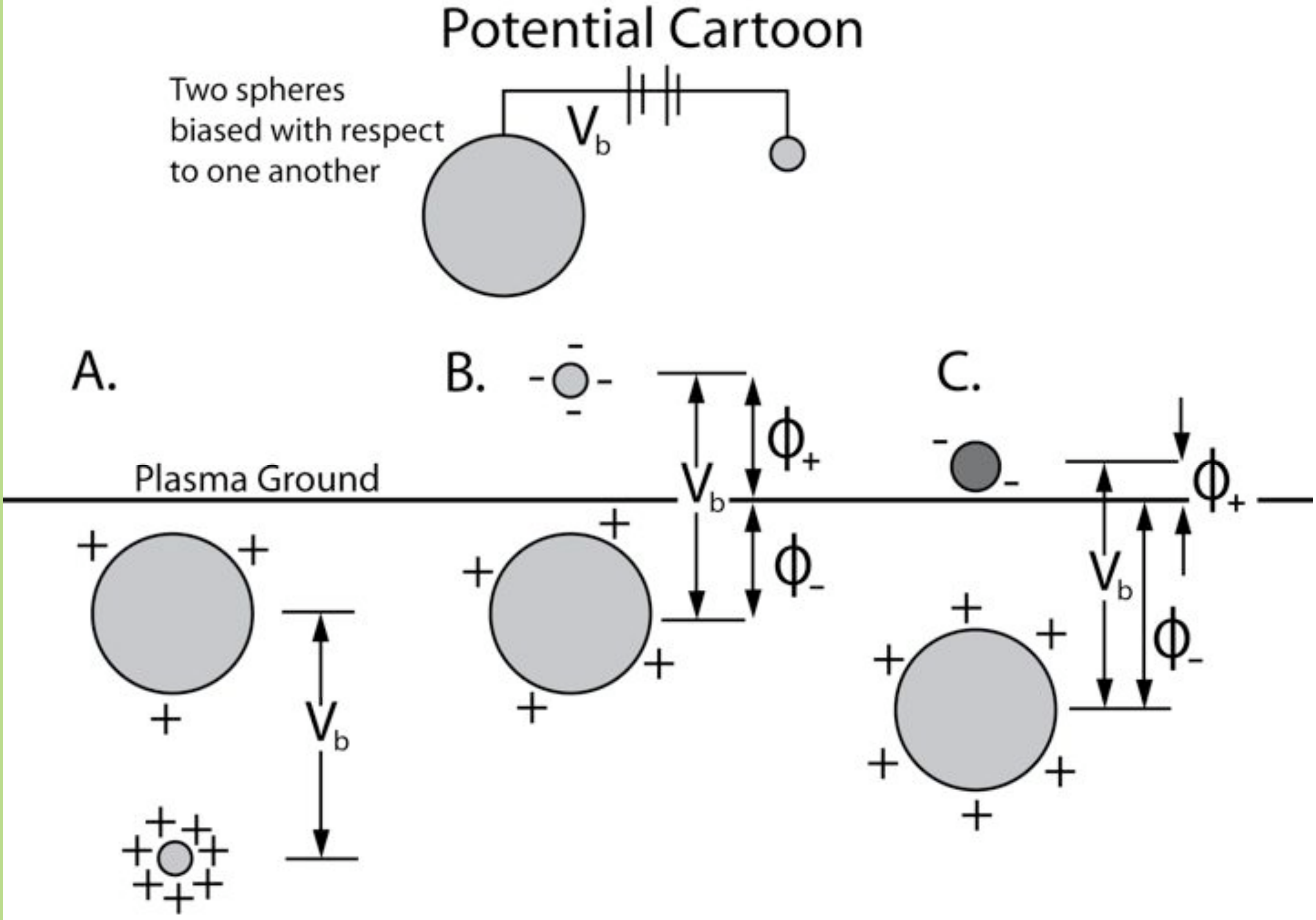
$$\phi(r) = \phi_{cyl} \exp\left(\frac{-|r|}{\lambda_D}\right)\left[1 - \alpha \ln\left(\frac{|r|}{r_{cyl}}\right)\right] + \phi_p$$

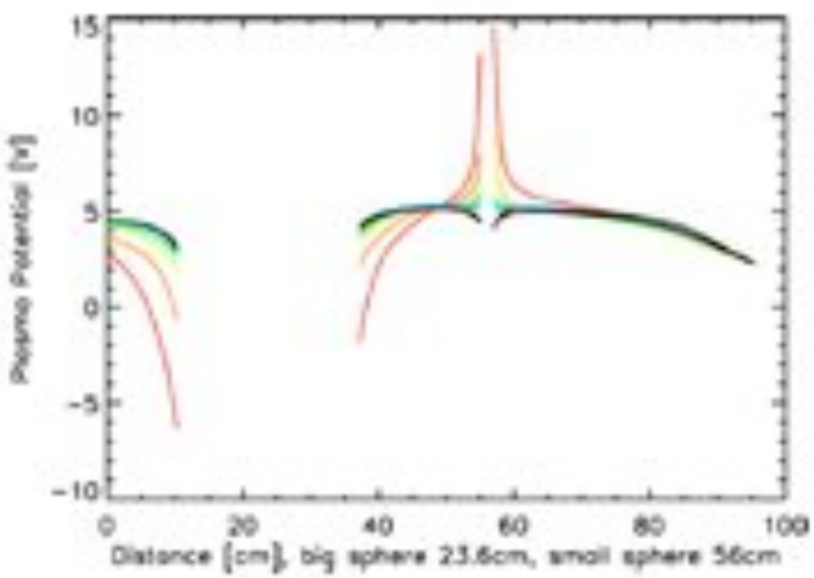
Ionospheric experiment

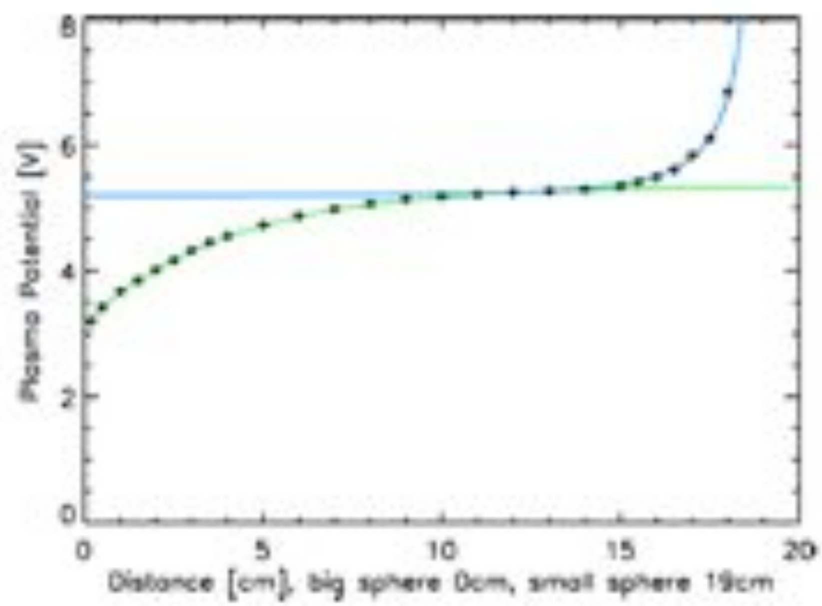


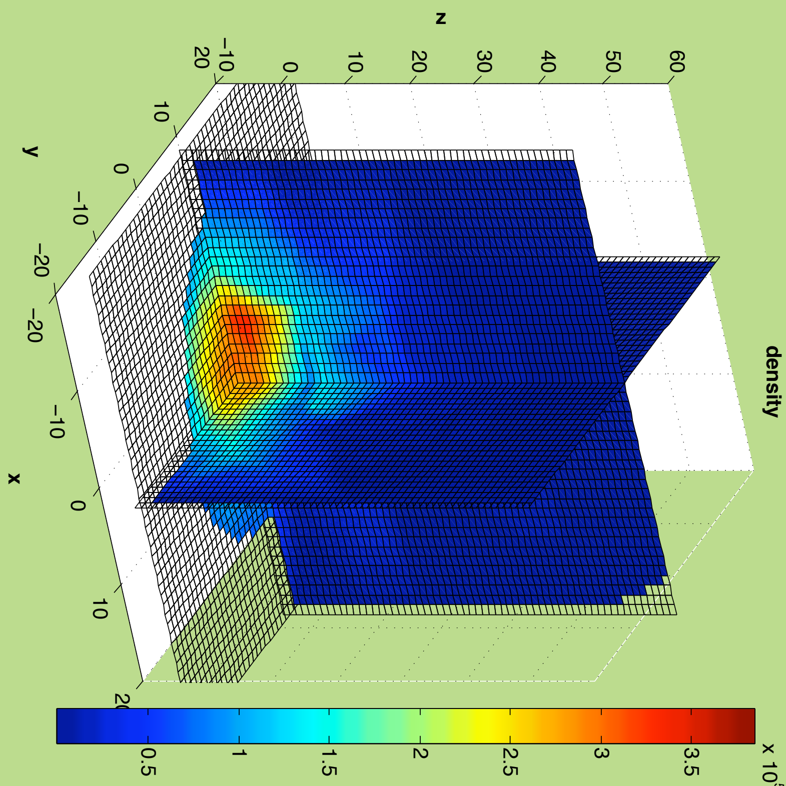
Sounding rocket payload analogy: payload floats negative and detector biased upward.

Lab experiment



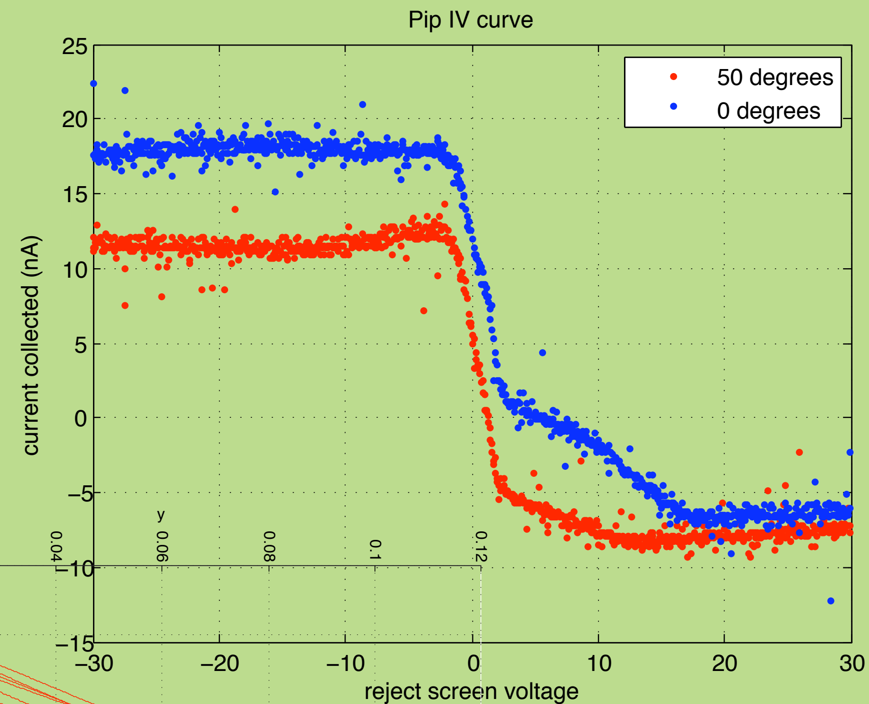

Plasma Potential [V]
Distance [cm], big sphere 23.6cm, small sphere 56cm

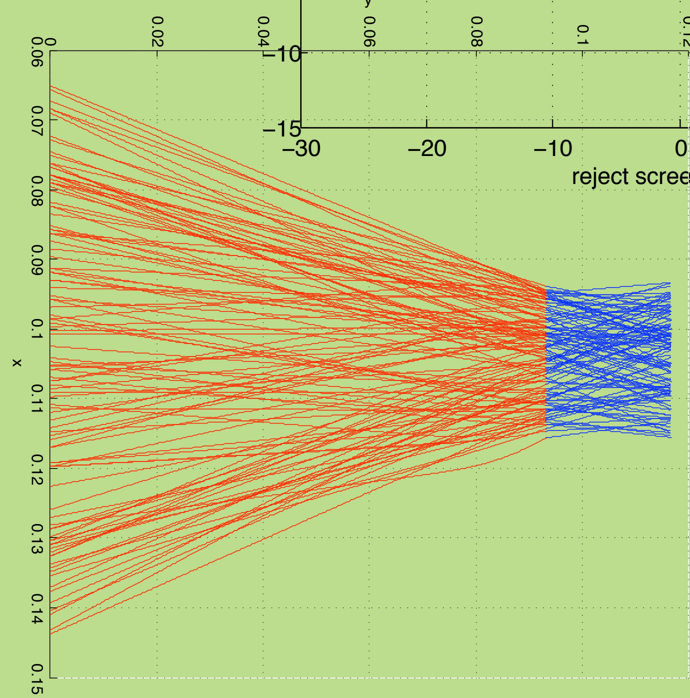

Plasma Potential [V]
Distance [cm], big sphere 0cm, small sphere 19cm


z
y
x
density
x 10^5

Ionospheric thermal plasma facility

- Mapping and understanding the plasma flow
- Using the flow to quantify the PIP response
- Trying a modified ESA for comparison
- How is the ion distribution perturbed by the sensor and sheath?
- Put whole RocketCube in the flow!





Possible experiments

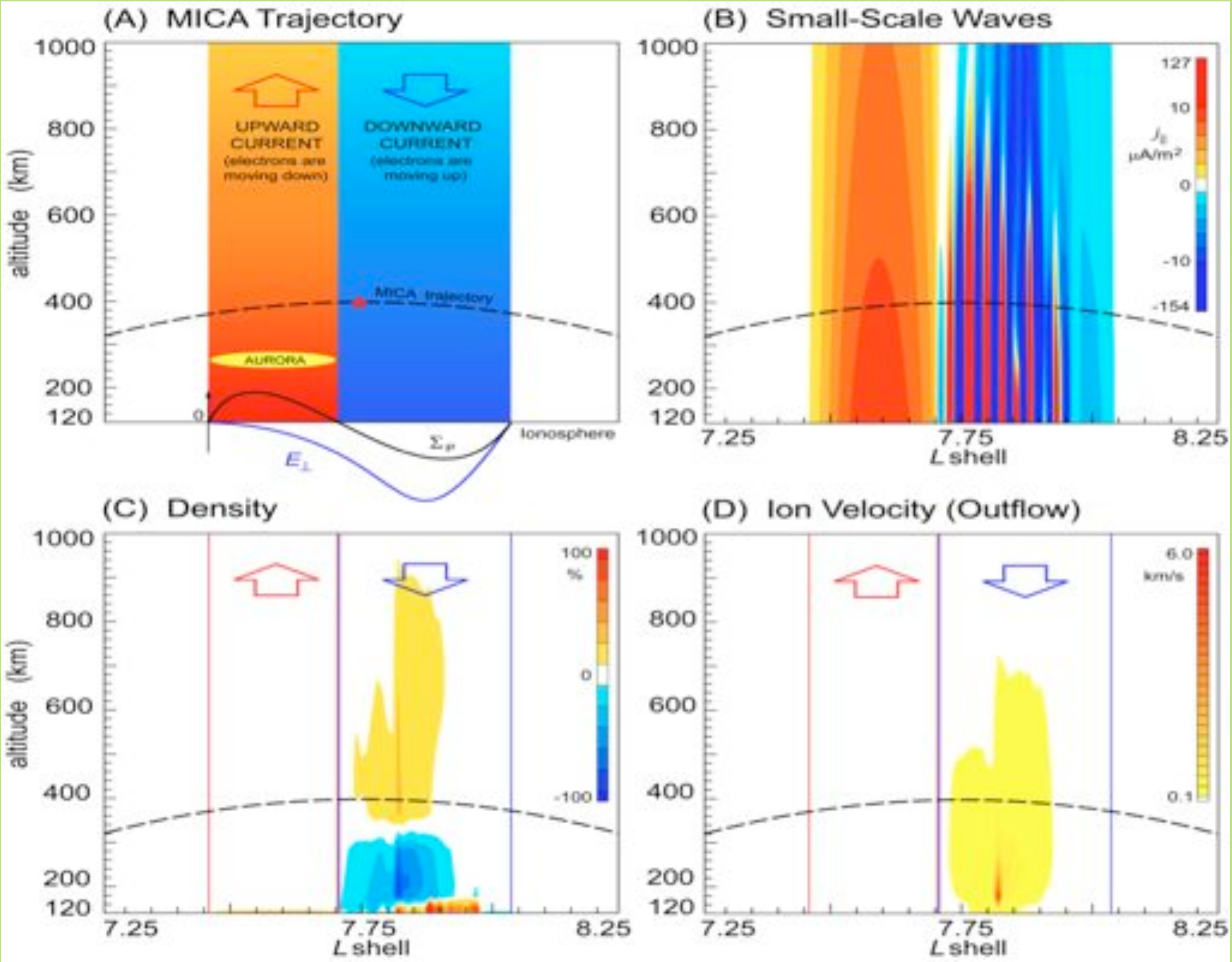
- Time-dependent sheath studies
- Sheaths with and without booms of varying lengths
- k-spectrum of density irregularities over AMISR: many subpayloads from a rocket
  - Requires small spacecraft development
  - Density, mag, GPS
  - Balloon test flight this summer, JPL rocket proposal

Outline

- Aurora
- Ionosphere
- Plasma
- ***Processes***
  - **IAR and other feedback**
  - **Heating and thermal response**
  - **Gradients and response times**
  - **Collisional complications**
- Instrumentation and measurements
- Swarms

Jan Curtis

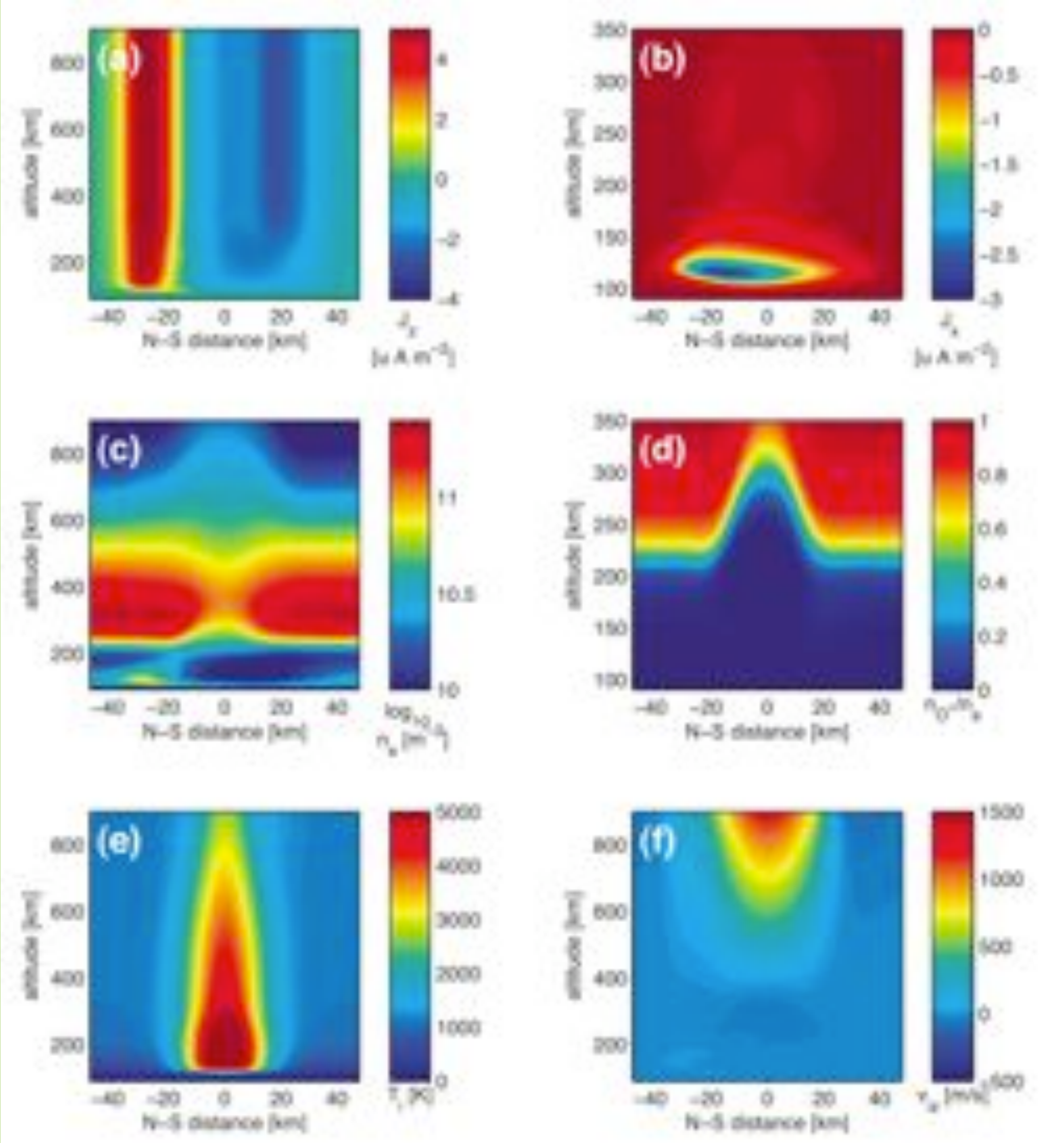
MICA rocket: study of ionospheric modulation by dark aurora



Model: Anatoly Streltsov, Dartmouth

Questions about ionospheric structuring and dynamics

- Zettergren and Semeter, 2012
- Effects of composition and collisions
- 2D electrostatic



Probe physics:

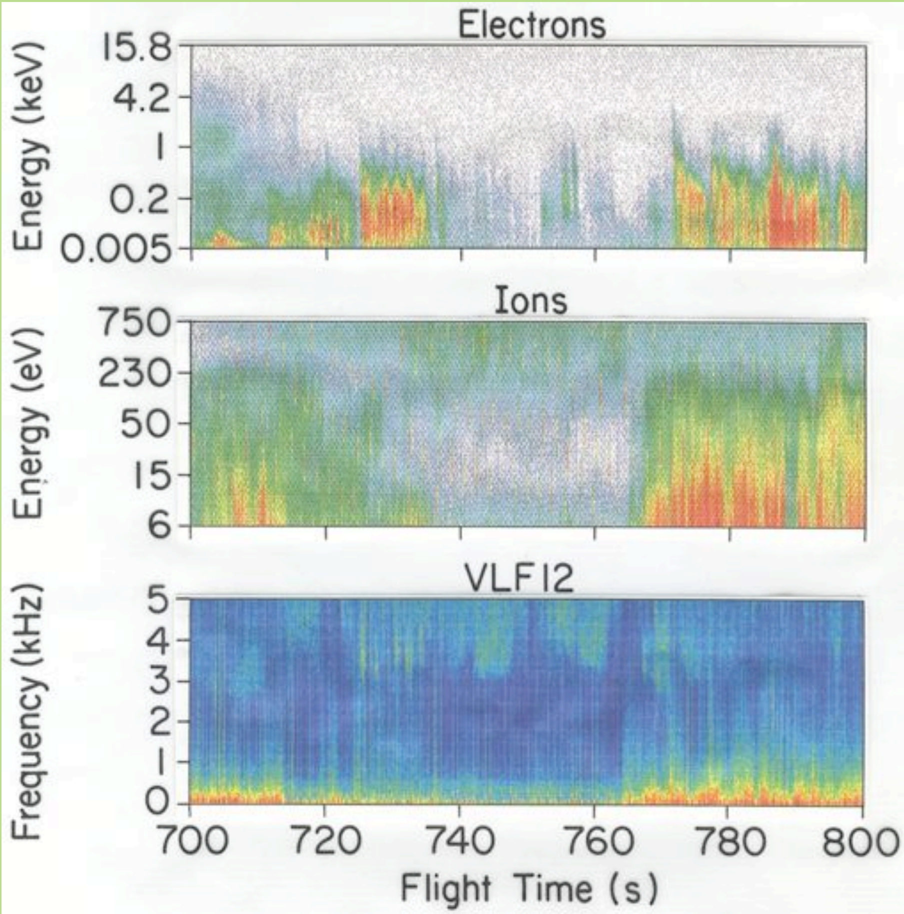
Anything non-homogeneous, non-isotropic, non-time-stationary will cause a sheath to launch ion-acoustic-like waves

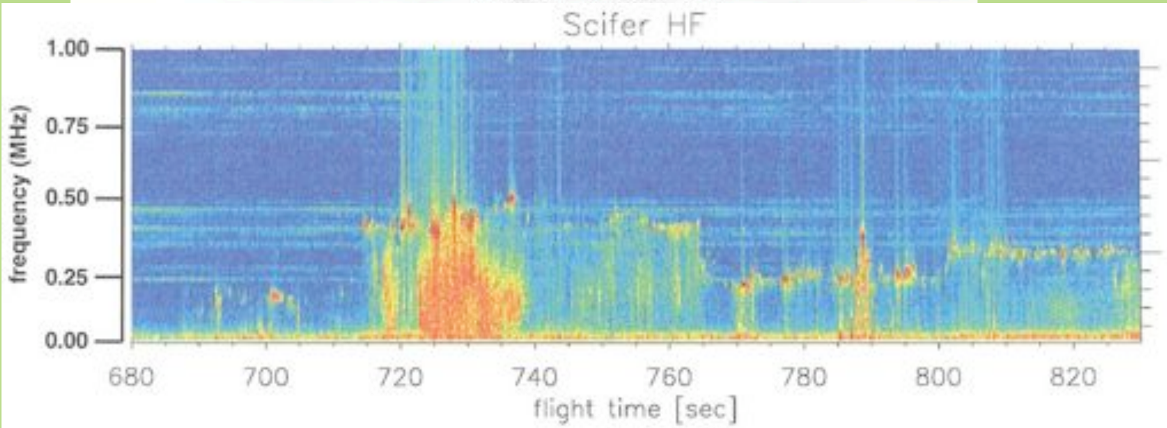
[Montgomery, 1971]

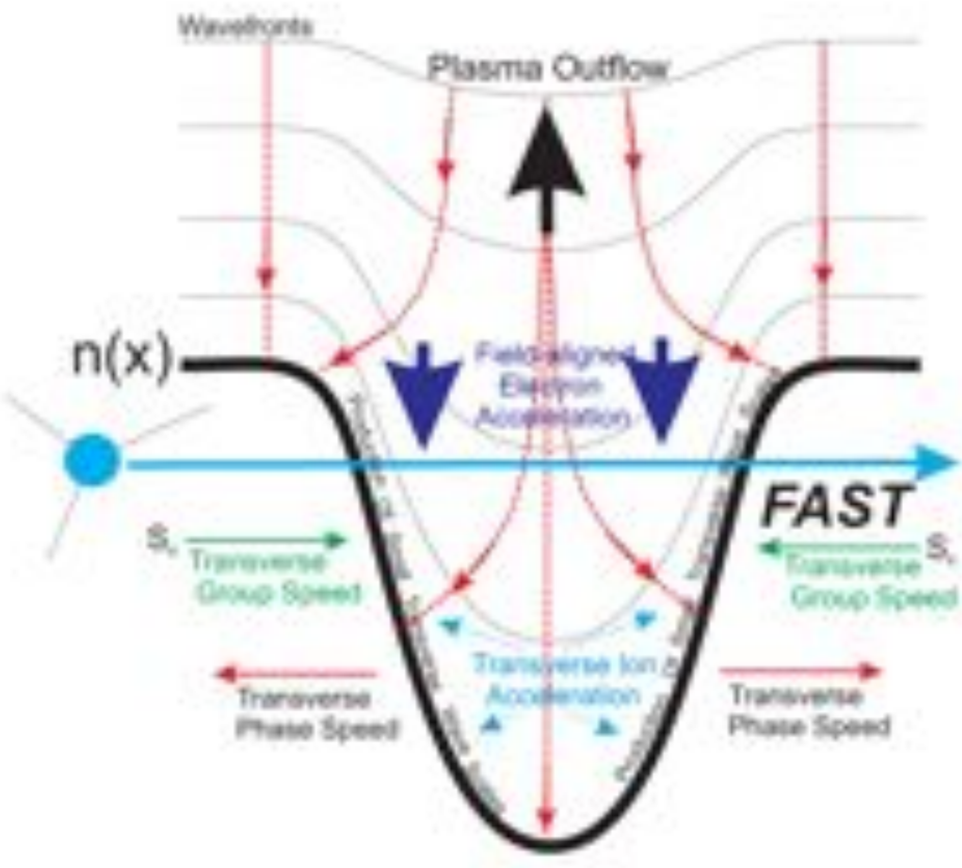
Drag a biased probe/payload across a density irregularity and get waves generated by the sheath?

SCIFER-1 Science

TAI, VLF in a density hole

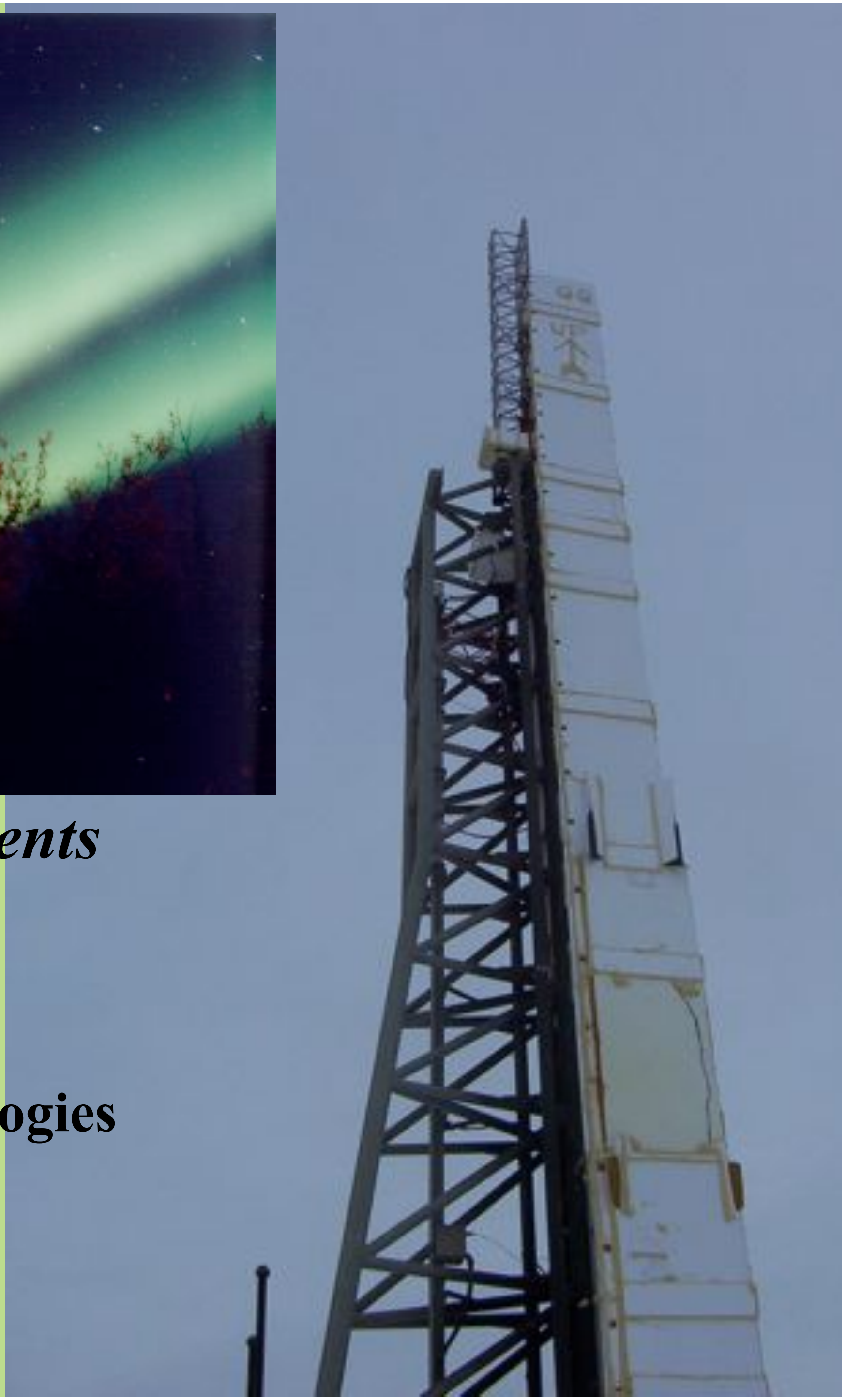






Chaston interpretation of BBELF also
involves density holes

Outline



- Aurora
- Ionosphere
- Plasma
- Processes
- ***Instrumentation and measurements***
  - **Heritage plasma instruments**
  - **Low resource PIP**
  - **Arduino controllers**
  - **Commercially available technologies**
- Swarms

Question

What interesting questions can be addressed with truly low-resource spacecraft?

Miniaturization and low resources:

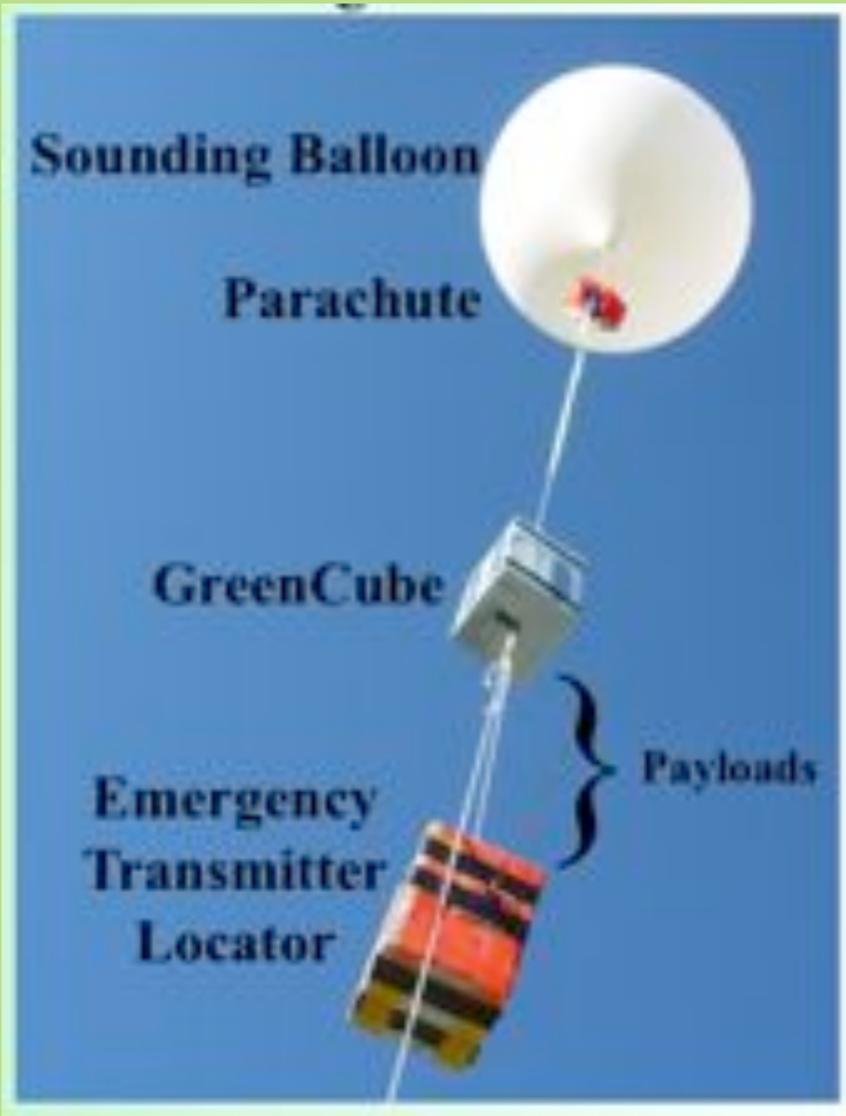
Challenge: what can you do with really low resources?
EDI can't go there…geometry factor if nothing else
Dust detector 1 was bigger than the CubeSat!
Some things can be miniaturized

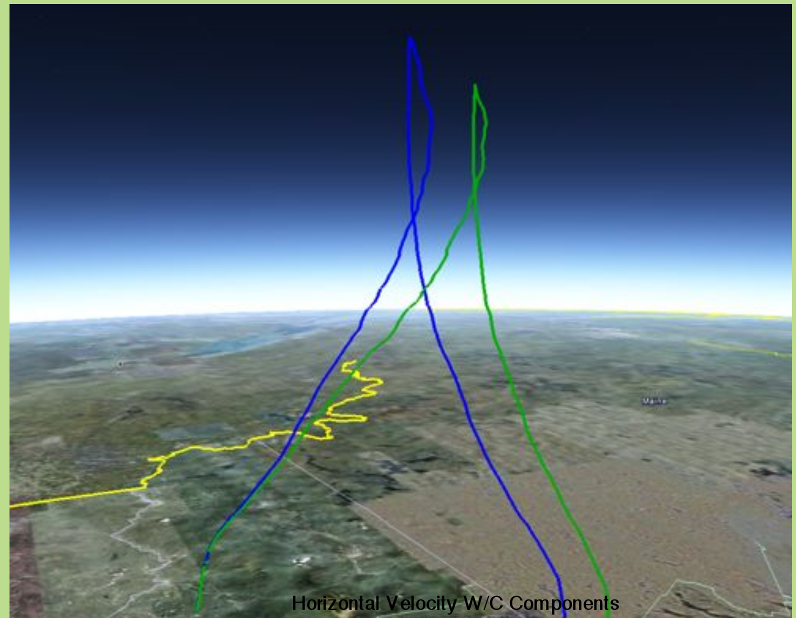
Receivers
Thermal fluxes
Arrays of payloads
Multipoint measurements

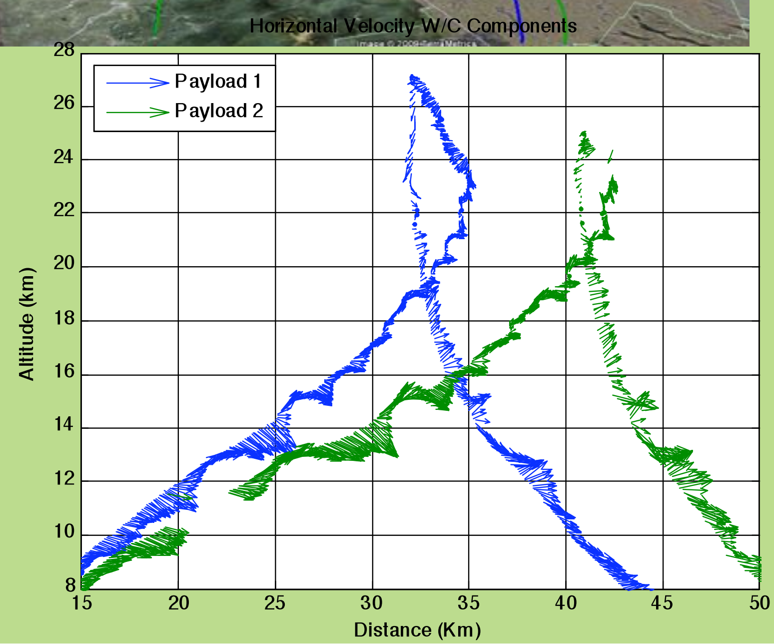
GreenCube, RocketCube, RocketProbe

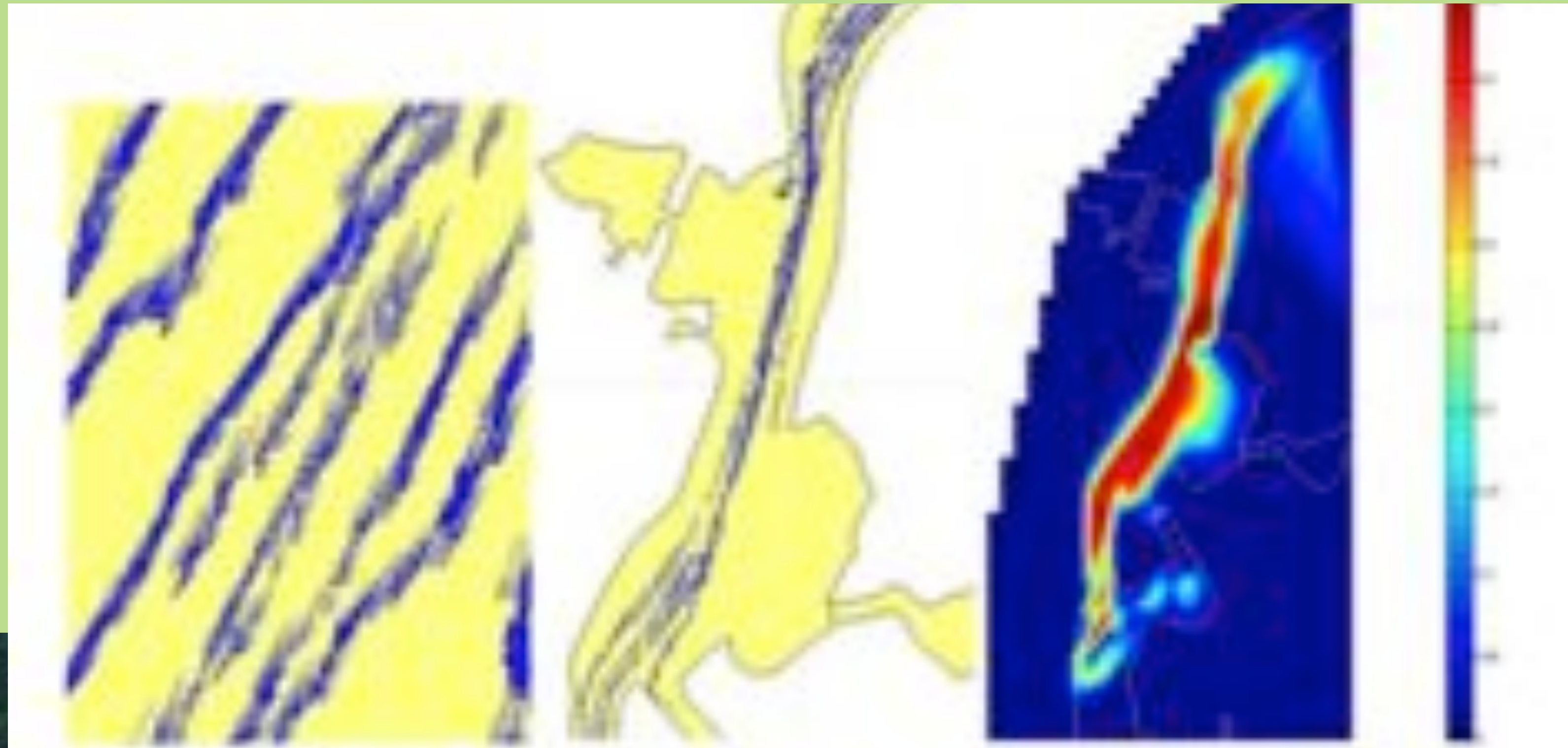
- *GreenCube*: undergraduate balloon-borne CubeSat program sponsored by JPL-SURP
- Instrumented telemetered sensorcraft for atmospheric and astronomical science
- Student-driven, student-run
- 8 students, 2-3 balloons per year
- GPS, Mag, sensors, radios

GreenCube, RocketCube, RocketProbe



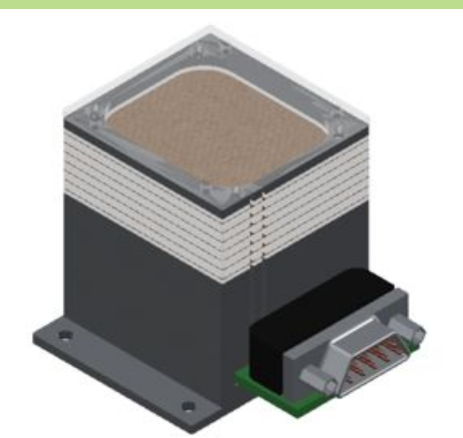


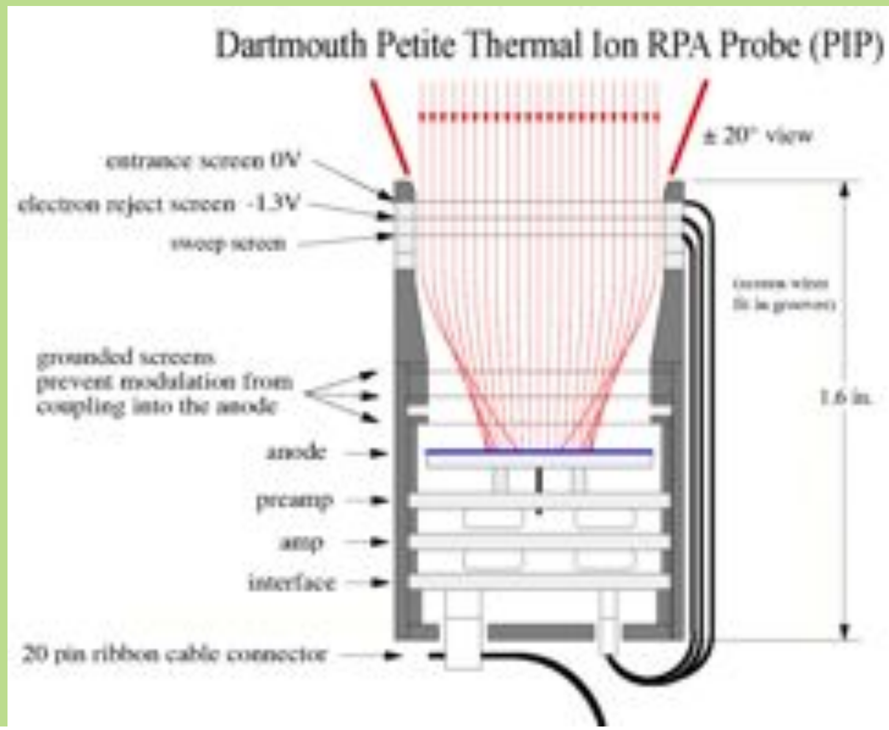




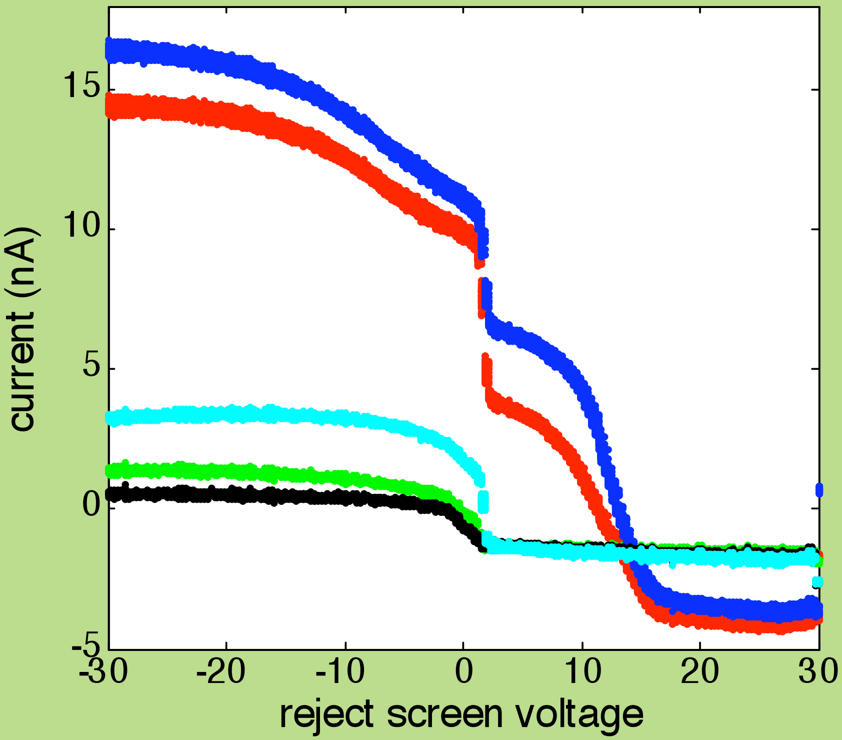
Sheaths and charging

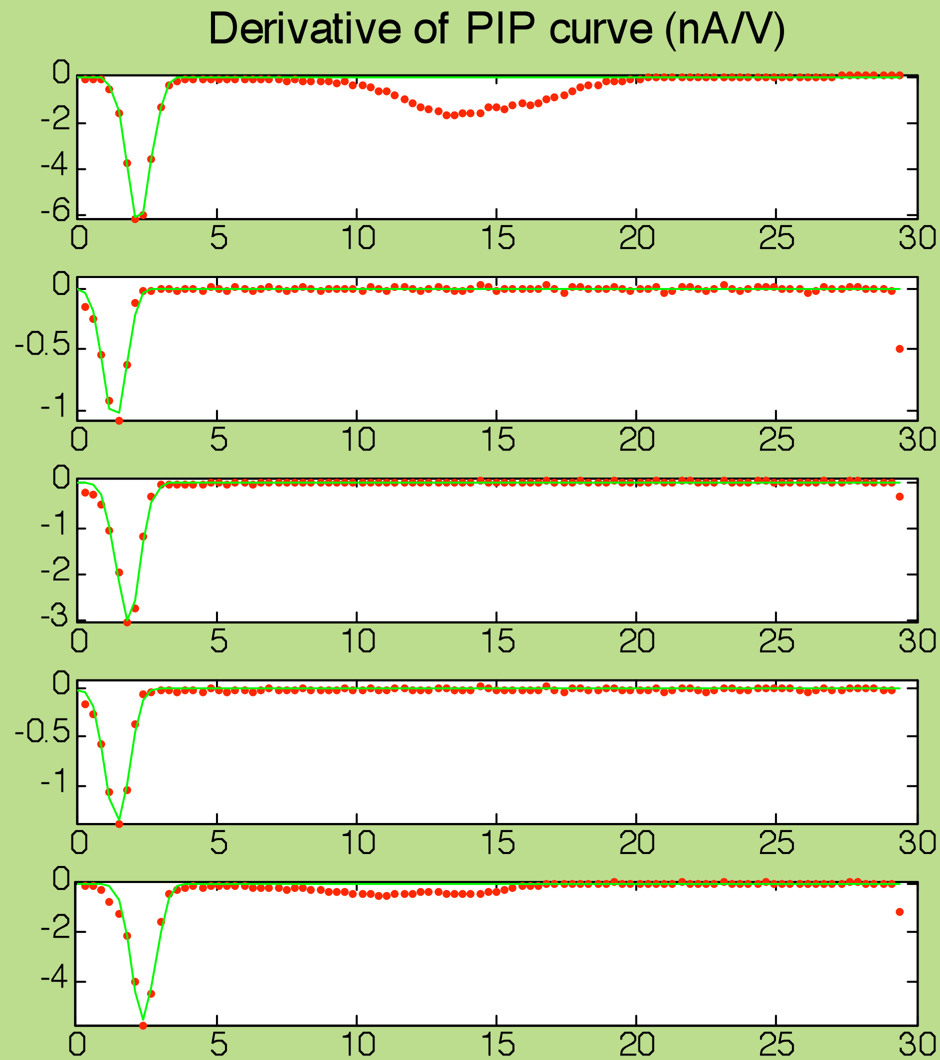
- Ion RPA which does not reject e- current: payload ground = net zero current
- Full ion distribution has access for $\phi_{sc}<0$
- Collimated for direction sensitivity
- Subsonic vs supersonic



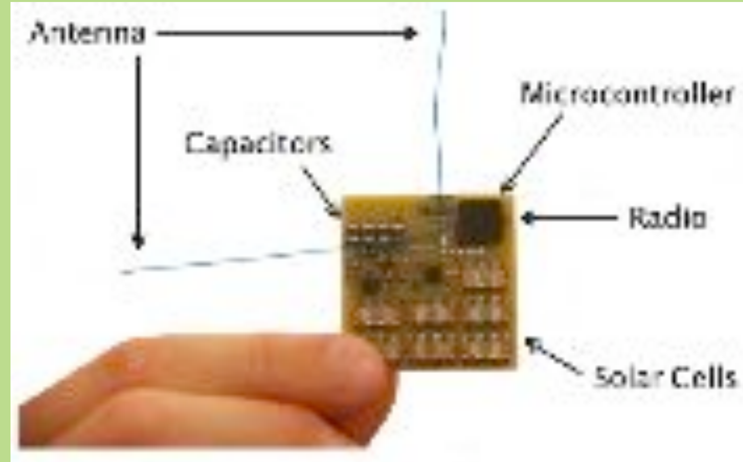


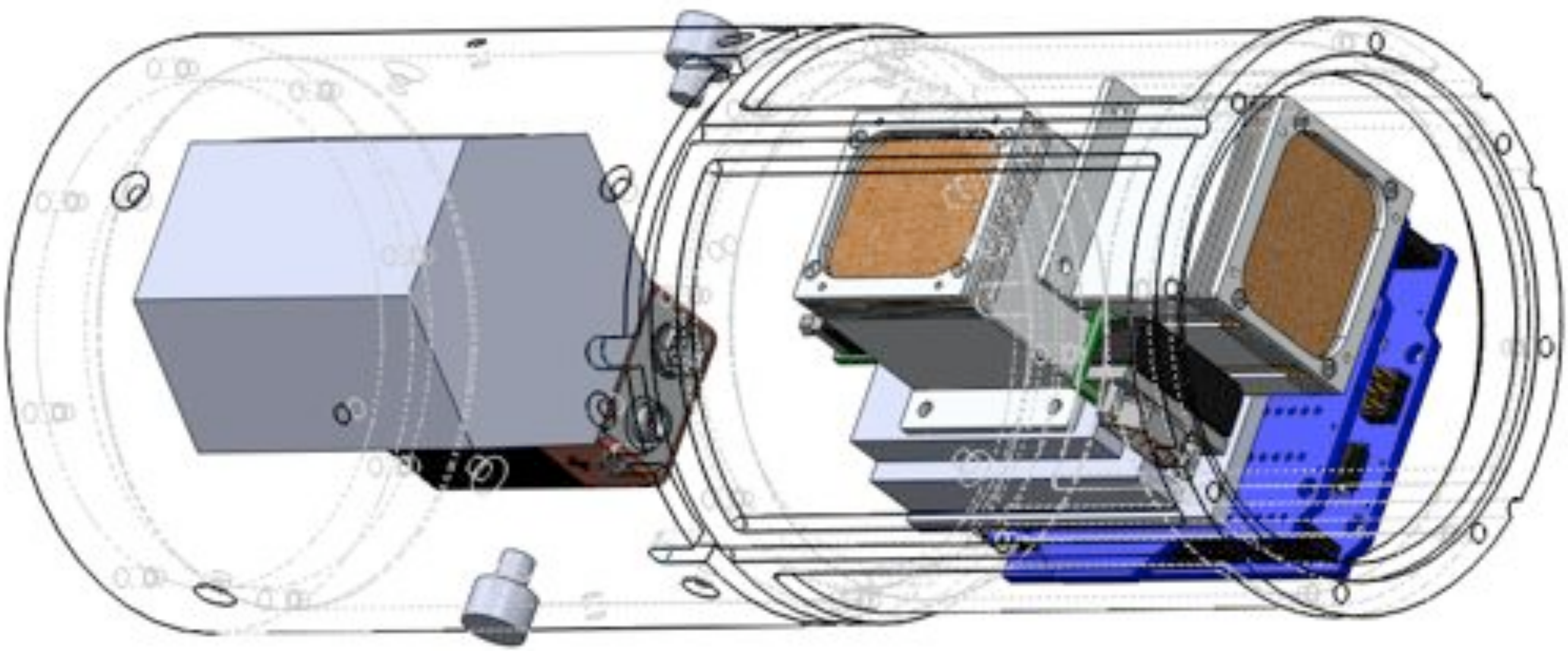
PIP Ion Testing





Lisa Gayetsky

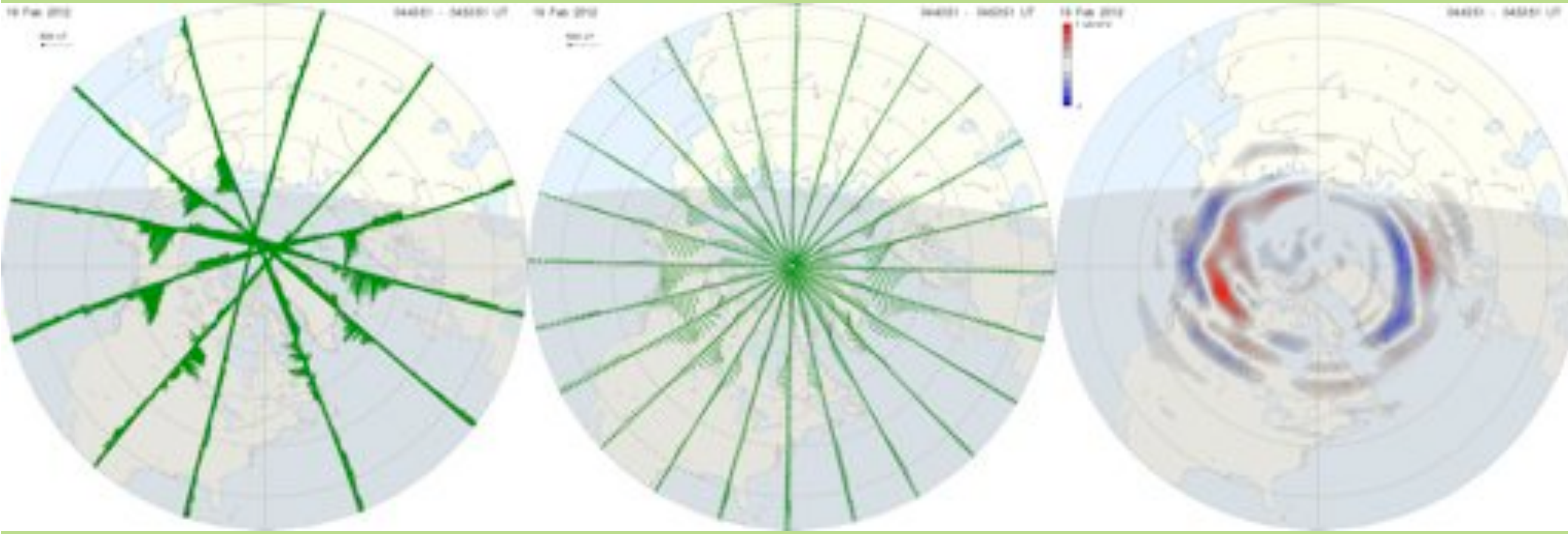

Antenna
Microcontroller
Capacitors
Radio
Solar Cells



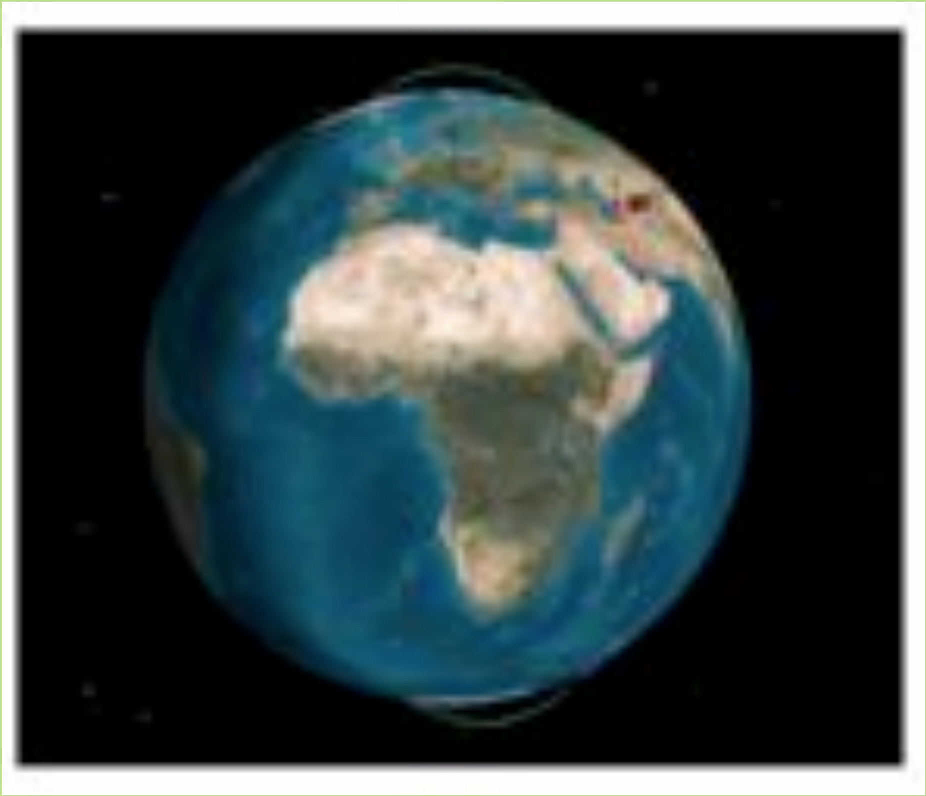
Outline

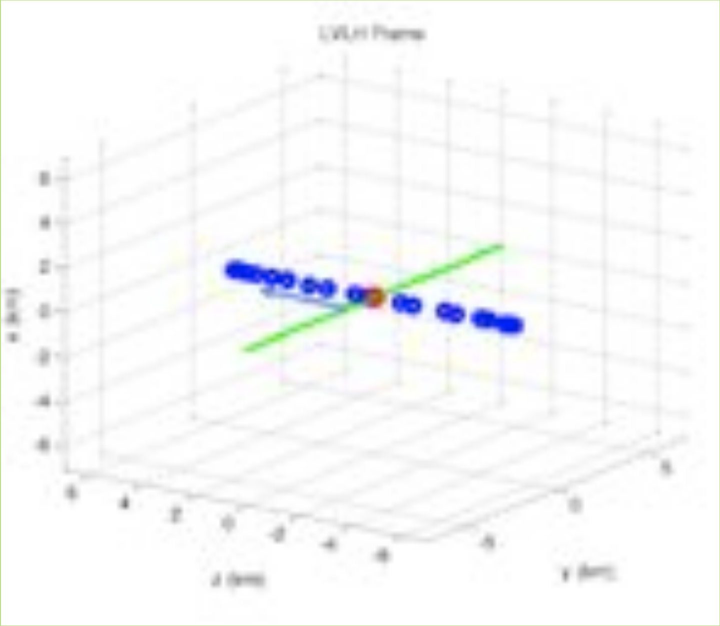
Jan Curtis

- Aurora
- Ionosphere
- Plasma
- Processes
- Instrumentation and measurements
- ***Swarms***
  - **Put it all together:**
    - **Auroral ionosphere orbits**
    - **Low resource spacecraft**
    - **Gradients and dynamics: multipoint measurements**
    - **Swarms of Cubesat-class spacecraft**



JHU/APL Ampere project





Sean Currey

Outline

Jan Curtis

- Aurora
- Ionosphere
- Plasma
- Processes
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www.dartmouth.edu/~aurora