A photograph taken from the International Space Station (ISS) showing the Earth's surface and the aurora borealis. The aurora is a vibrant green light display in the upper atmosphere, appearing as a series of horizontal bands and vertical streaks. The Earth's surface below is dark, with some cloud patterns visible. The ISS structure, including solar panel arrays, is visible in the foreground on the left side.

Auroral Charging and Characteristics of Auroral Charging Environments

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GEM Mini-Workshop
CEDAR-GEM Modeling Challenge Session
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Introduction

Today's presentation is a short tutorial on auroral charging of spacecraft and the characteristics of the space plasma environment that are required to predict charging

Outline

- Physics of surface charging
- Examples of auroral charging and auroral charging environments
- Electron, ion energy spectra during charging events
- Space weather model outputs required for predicting auroral charging

Acknowledgements:

DMSP SSJ, SSIES, and OLS records are provided by the US Air Force and NOAA's National Geophysical Data Center.



Potential Distributions on Spacecraft Surfaces

- **Electrostatic potentials**

- Due to net charge density on spacecraft surfaces of or within insulating materials due to current collection to/from the space environment
- Examples include
 - Plasma currents to surface
 - Secondary electron currents
 - Photoelectron currents
 - Solar array current collection
 - Active current sources (Electron, ion beams, electric thrusters, plasma contactors)
 - Energetic (~MeV) electrons

- **Electrodynamic (inductive) potentials**

- Modification of frame potentials without change in net charge on spacecraft
- Plasma environment not required
- Examples include
 - EMF generated by motion of conductor through magnetic field
 - Externally applied electric fields

Surface charging

$$\frac{dQ}{dt} = C \frac{d\phi}{dt} = \sum_k I_k \sim 0 \text{ at equilibrium}$$

Internal (deep dielectric) charging

$$\vec{\nabla} \cdot \vec{D} = \vec{\nabla} \cdot \epsilon \vec{E} = \vec{\nabla} \cdot \epsilon (-\vec{\nabla} \phi) = \rho$$

$$\nabla^2 \phi = -\rho/\epsilon$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \vec{J} \quad \text{where } \vec{J} = \vec{J}_R + \vec{J}_C$$

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad \text{Laboratory frame}$$

$$\vec{F}' = q\vec{E}' \quad \text{Spacecraft rest frame}$$

$$\vec{E}' = \vec{E} + \vec{v} \times \vec{B} \quad \text{Forces equal in both frames!}$$

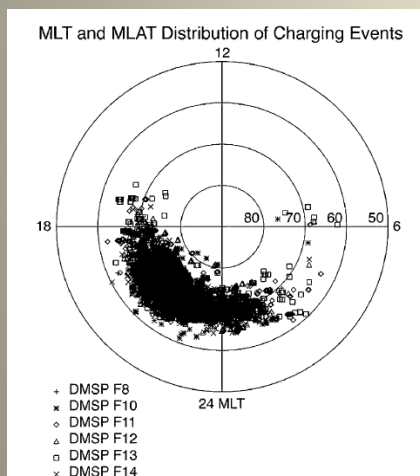
$$\epsilon'_m = \oint_C \vec{E}' \cdot d\vec{S} = \oint_C (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{S}$$

$$\Delta \phi' = \oint_C (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{S}$$

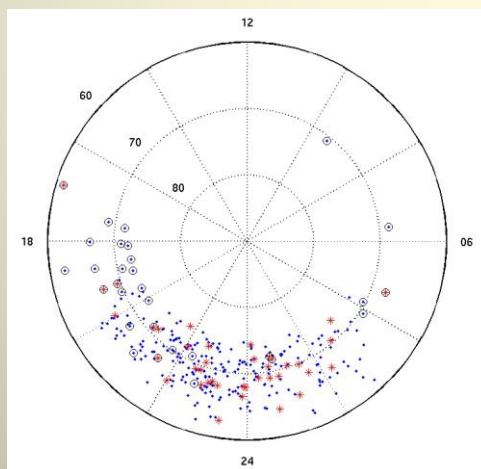
Auroral Charging Conditions

Necessary conditions for high-level (≥ 100 V) auroral charging*

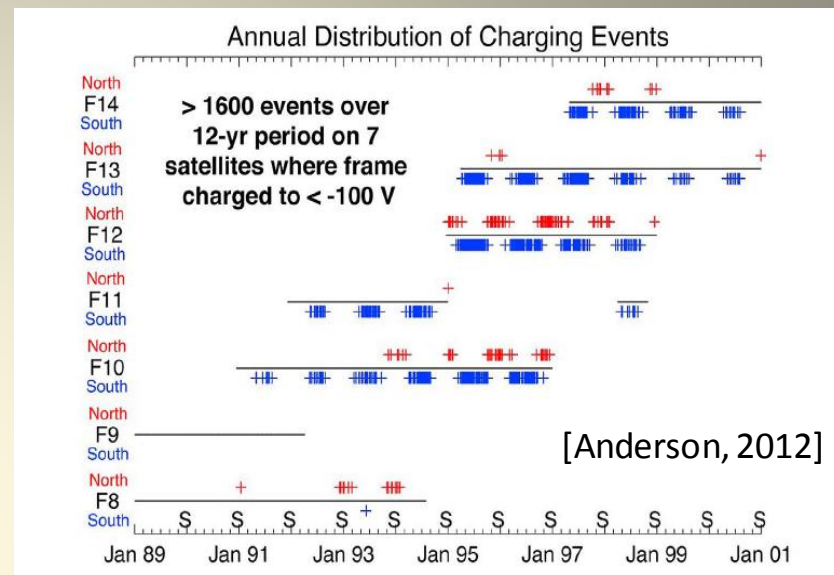
- No sunlight (or ionosphere below spacecraft in darkness)
- Intense electron flux $> 10^8$ e/cm²-s-sr at energies of 10's keV
- Low ambient plasma density ($< 10^4$ #/cm³)



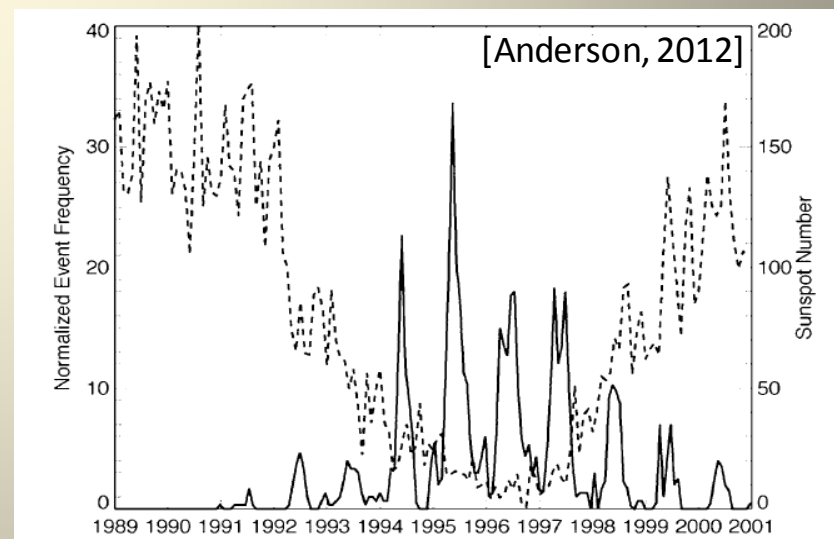
[Anderson, 2012]



[Eriksson and Wahlund, 2006]



[Anderson, 2012]



[Anderson, 2012]

*Gussenhoven et al., 1985; Frooninckx and Sojka, 1992; Eriksson and Wahlund, 2006.

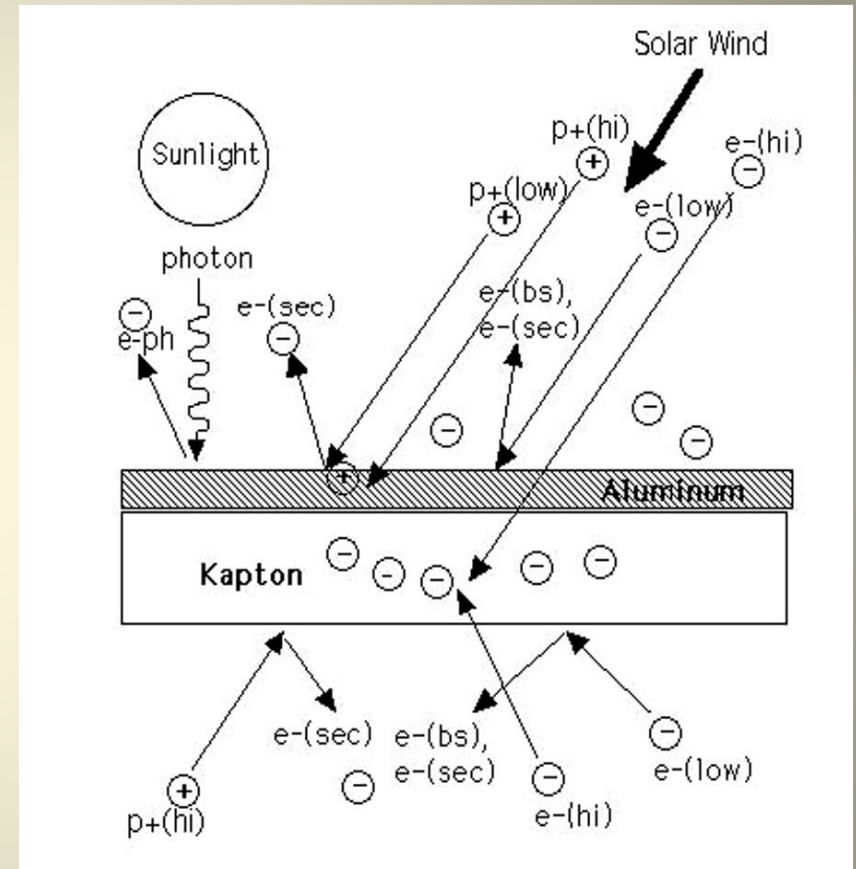
Surface Charging Physics

- Auroral charging is a process of balancing currents to and from spacecraft surfaces as a function of the spacecraft potential

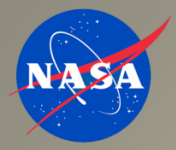
$$\frac{dQ}{dt} = C \frac{dV}{dt} = \frac{d\sigma}{dt} A = \sum_k I_k$$

$$\frac{dQ}{dt} = \sum_k I_k =$$

$+I_i(V)$	incident ions
$-I_e(V)$	incident electrons
$+I_{bs,e}(V)$	backscattered electrons
$\pm I_c(V)$	conduction currents
$+I_{se}(V)$	secondary electrons due to I_e
$+I_{si}(V)$	secondary electrons due to I_i
$+I_{ph,e}(V)$	photoelectrons



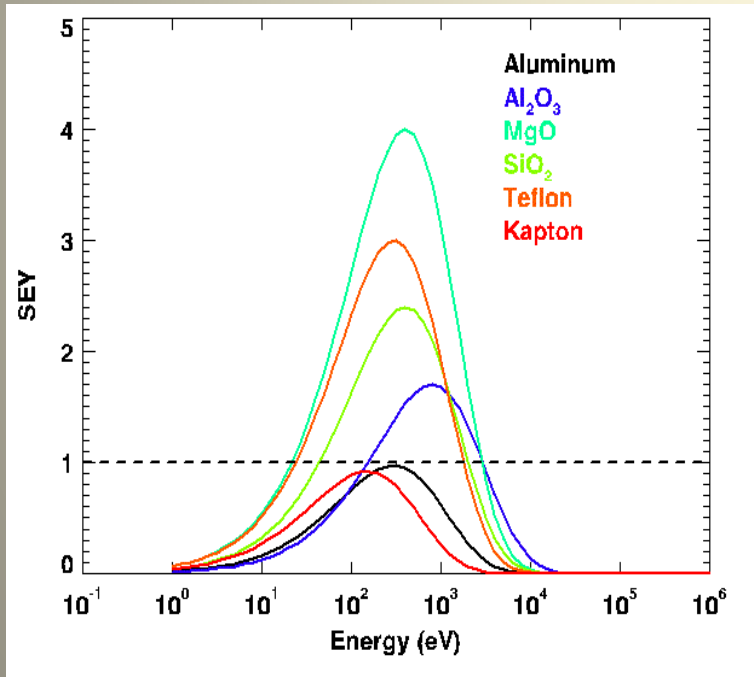
(Garrett and Minow, 2004)



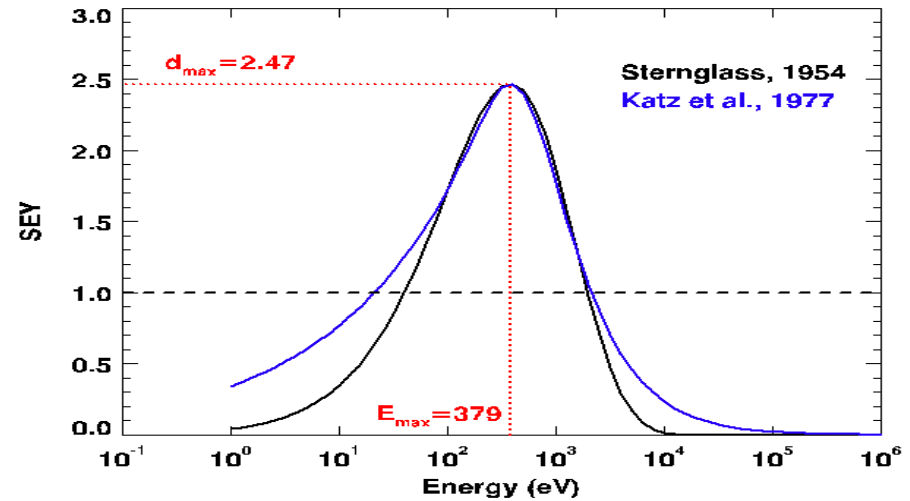
Secondary Electron Yields

Charging is suppressed when $SEY > 1$

$$\begin{aligned} \frac{dQ}{dt} &= \sum_k I_k = +I_i - I_e + I_{se} + I_{ph,e} \\ &= +I_i - I_e(1 - \delta) + I_{ph,e} \end{aligned}$$



δ_m, E_m from Hasting and Garrett, 1996

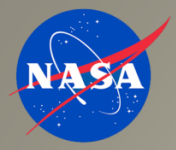


Sternglass, 1954

$$\delta_e(E, \theta) = \delta_{e,max} \frac{E}{E_{max}} \exp\left(2 - 2\sqrt{\frac{E}{E_{max}}}\right) \exp[2(1 - \cos \theta)]$$

Katz et al., 1977; Whipple, 1981

$$\delta_e(E, \theta) = \frac{1.114\delta_{e,max}}{\cos \theta} \left[\frac{E}{E_{max}} \right]^{0.35} \left\{ 1 - \exp \left[-2.28 \cos \theta \left[\frac{E_{max}}{E} \right]^{1.35} \right] \right\}$$

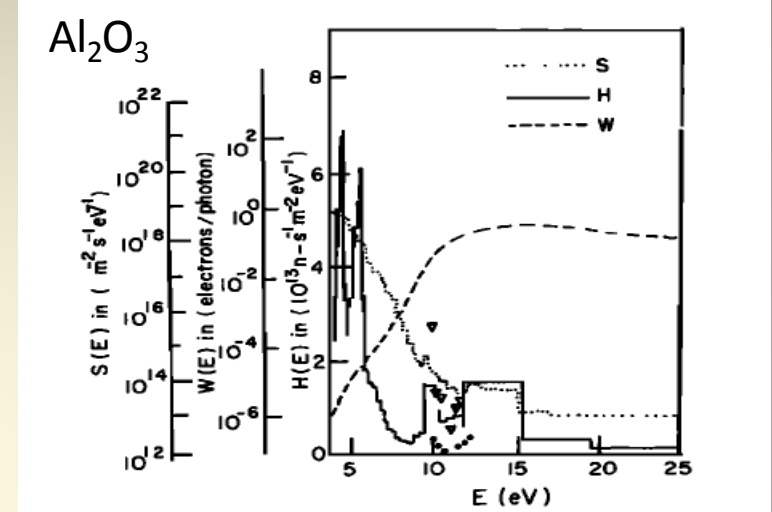


Photoemission Yields

- Photoemission is an important factor in controlling surface charging

Material	Saturation Photocurrent Density
Al ₂ O ₃	4.2 nA/cm ²
Au	2.9 nA/cm ²
Stainless steel	2.0 nA/cm ²
Graphite	0.4 nA/cm ²

[from Garrett, 1981]



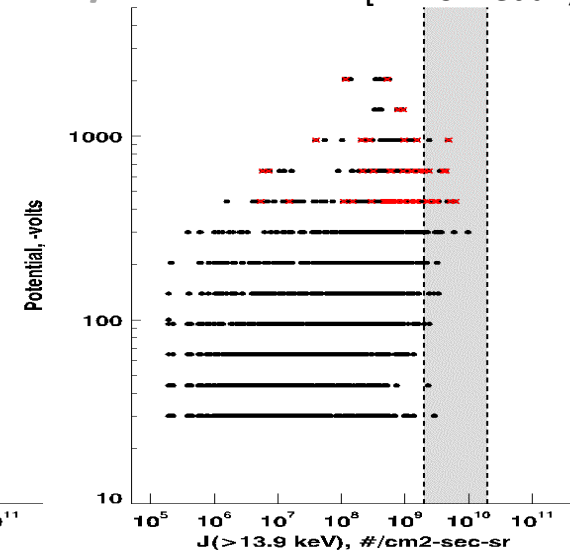
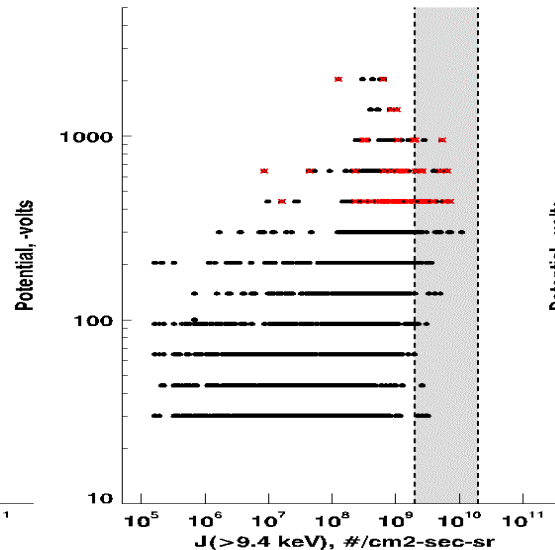
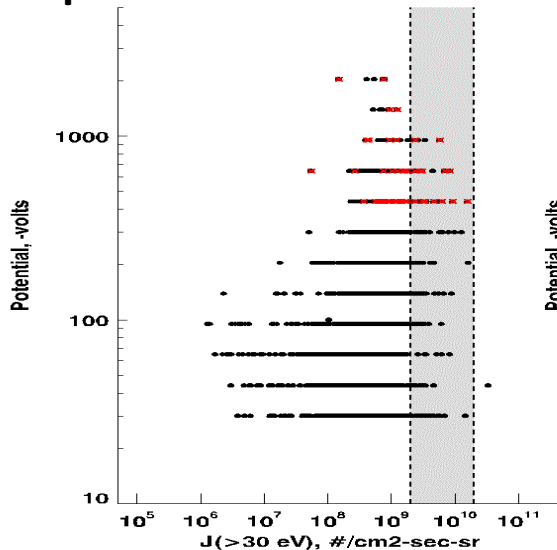
[Grard, 1973]

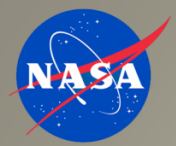
All potentials in event

Maximum Potential

1-10 nA/cm²

[Minow et al., 2014]



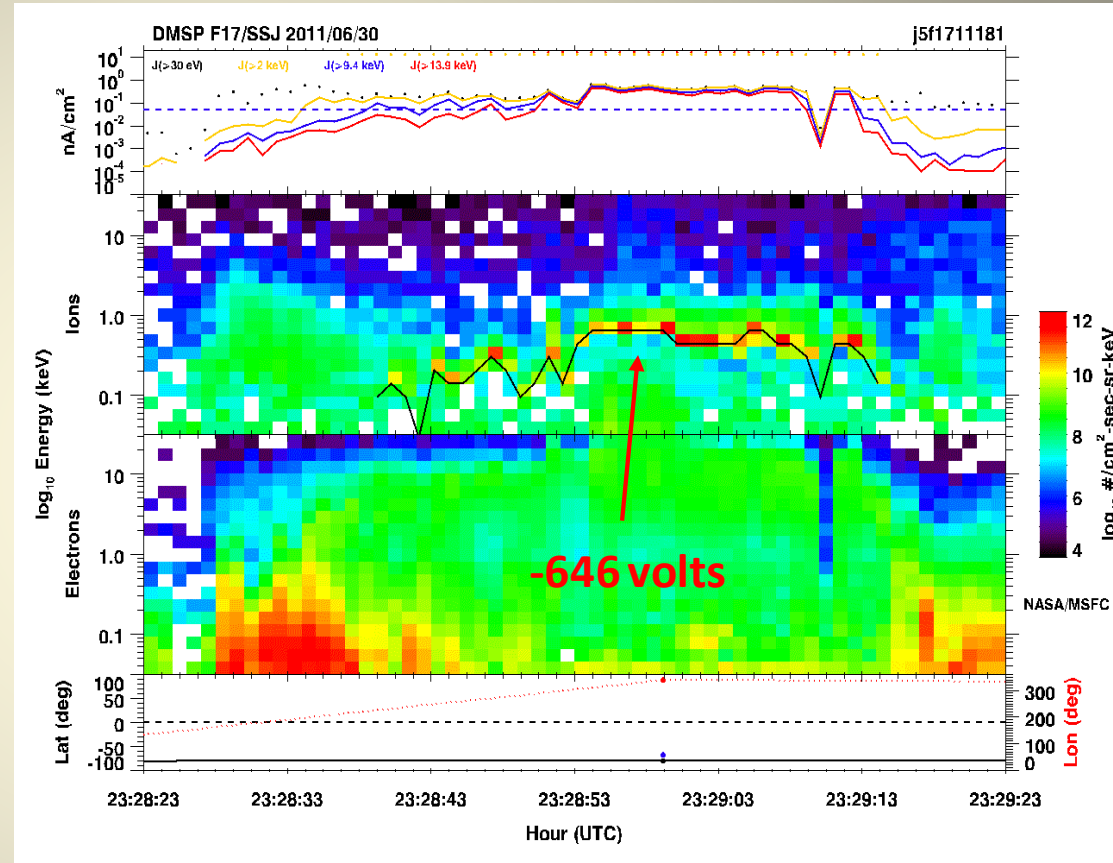


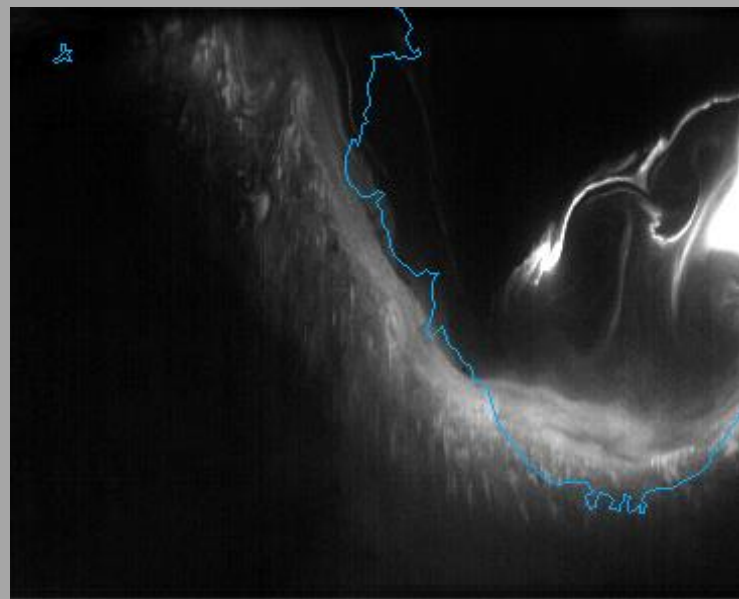
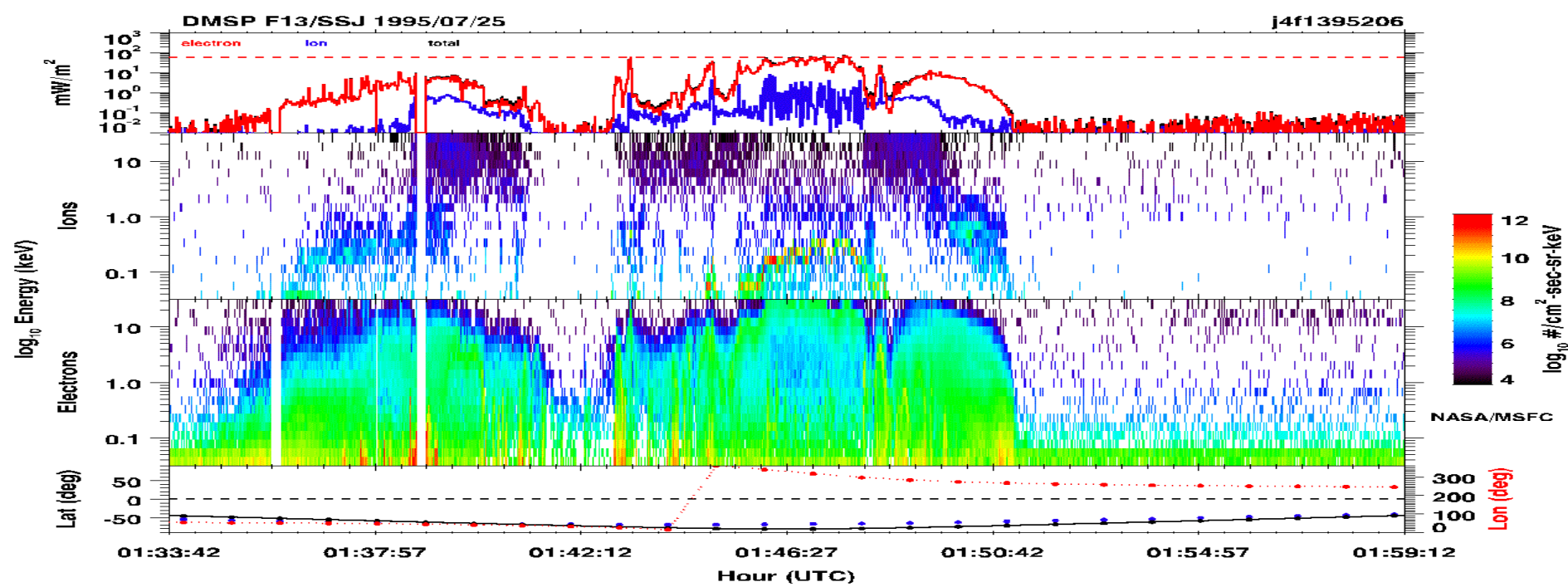
“Ion Line” Charging Signature

- Low energy ($E_0 \sim 0$) background ions accelerated by the spacecraft potential show up as sharp “line” of high ion flux in single channel

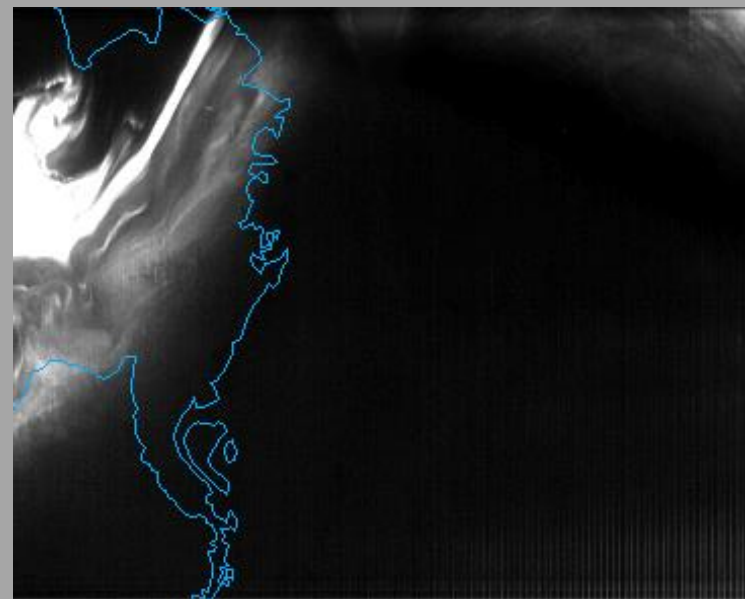
$$E = E_0 + q\Phi$$

- Assume initial energy $E_0 = 0$ with singly charge ions (O^+ , H^+) and read potential (volts) directly from ion line energy (eV)
- DMSP SSJ4, SSJ5 detectors
 - Electrons: 20 channels
30 eV to 30 keV
 - Ions: 20 channels
30 eV to 30 keV
 - Nominal channel energies used for this work



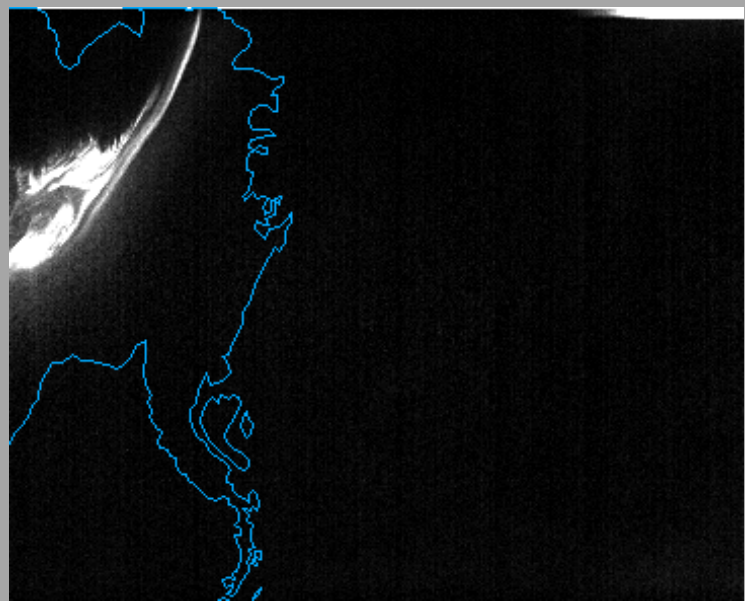
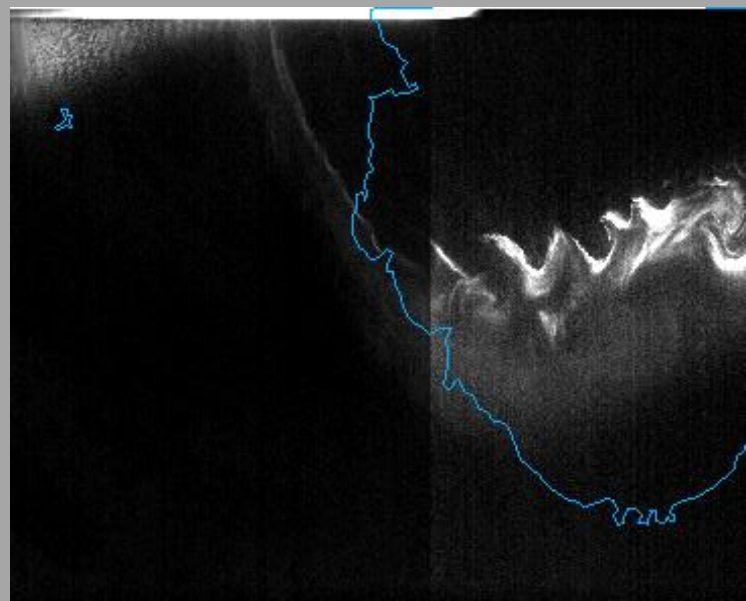
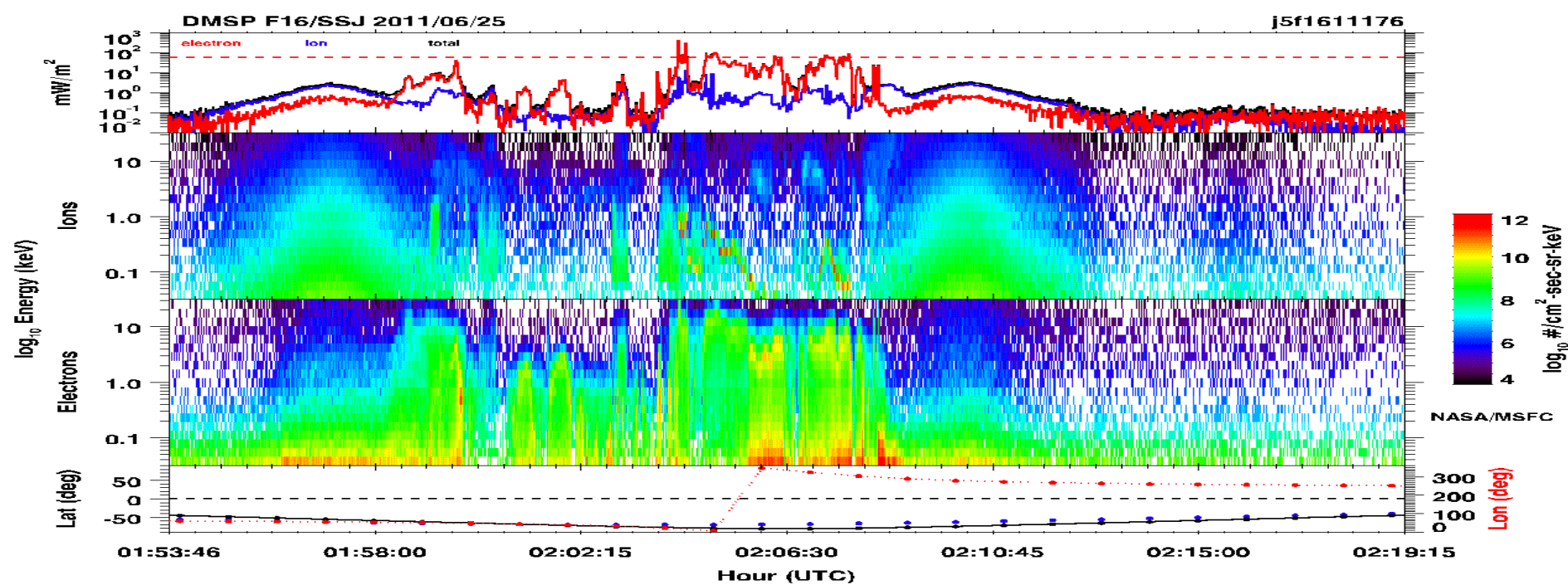


1995-07-25 01:33:42.0



1995-07-25 01:46:27.0

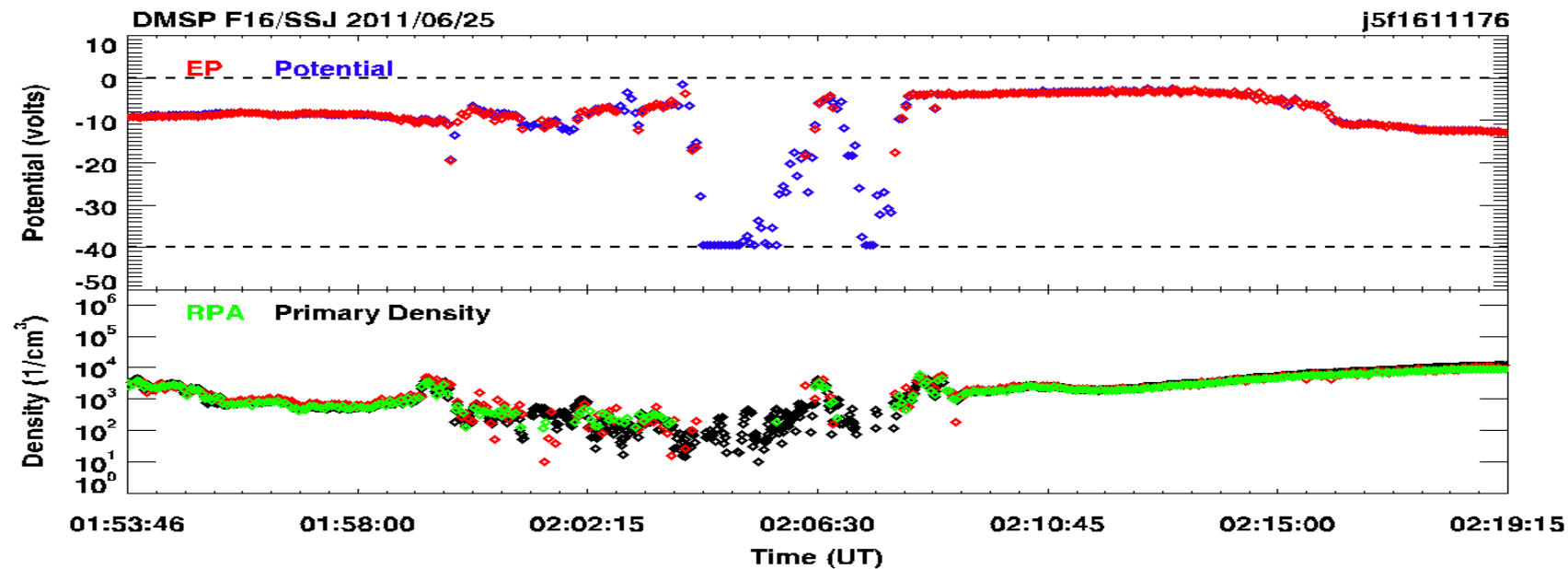
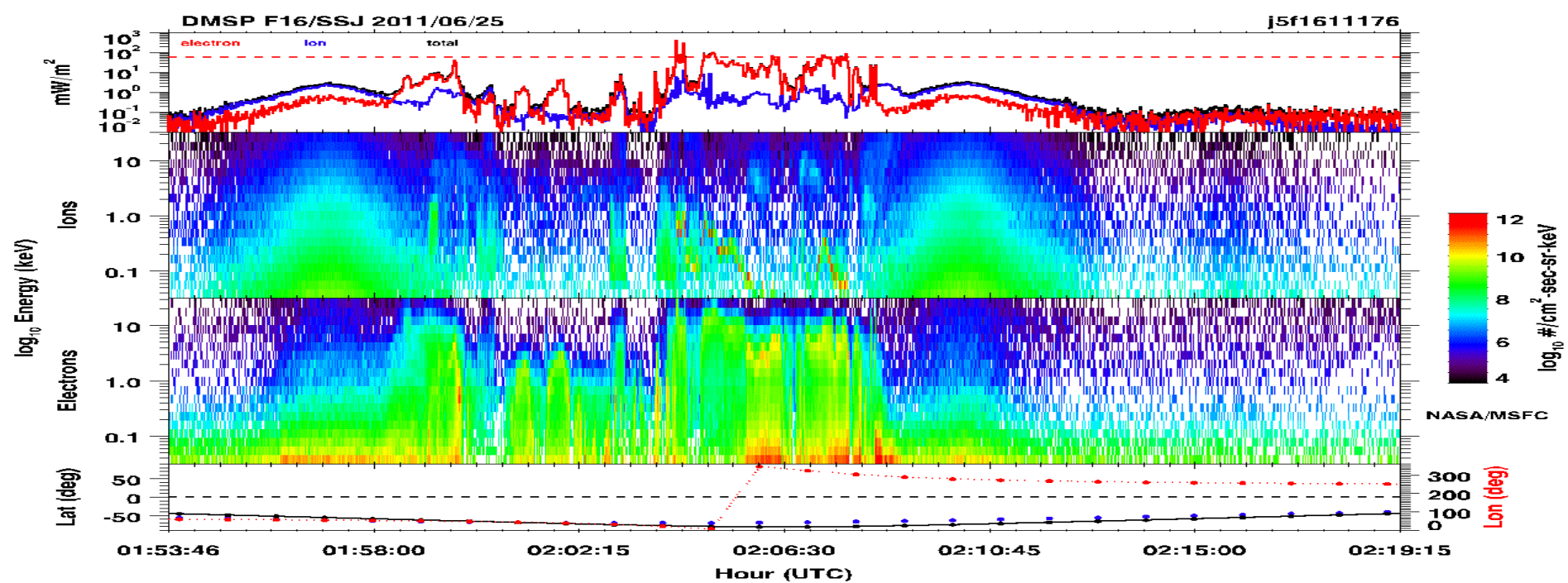
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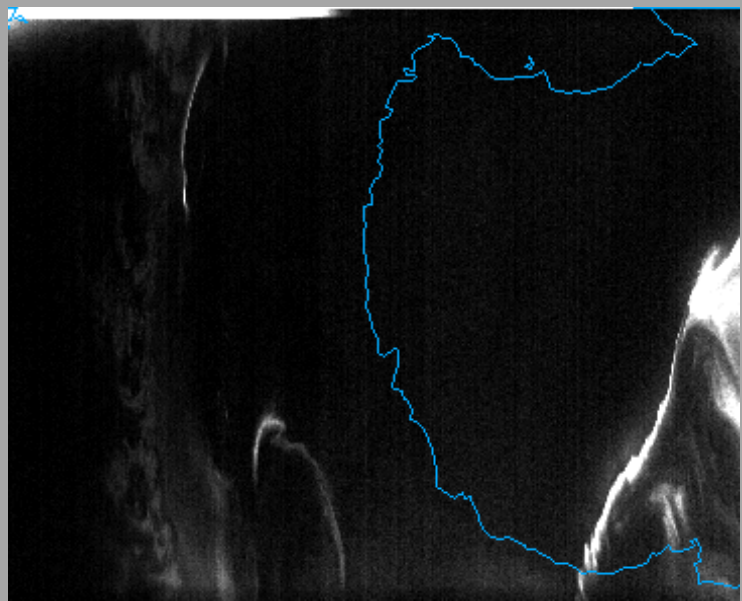
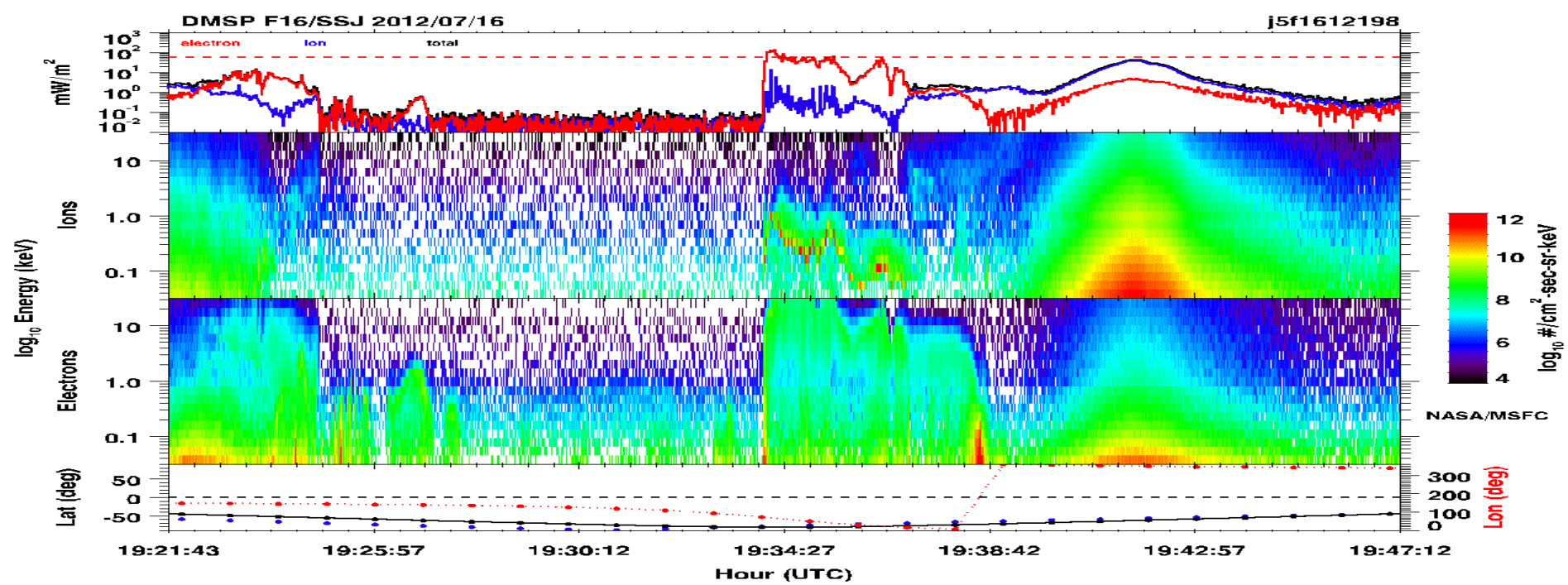


2011-06-25 01:53:46.0

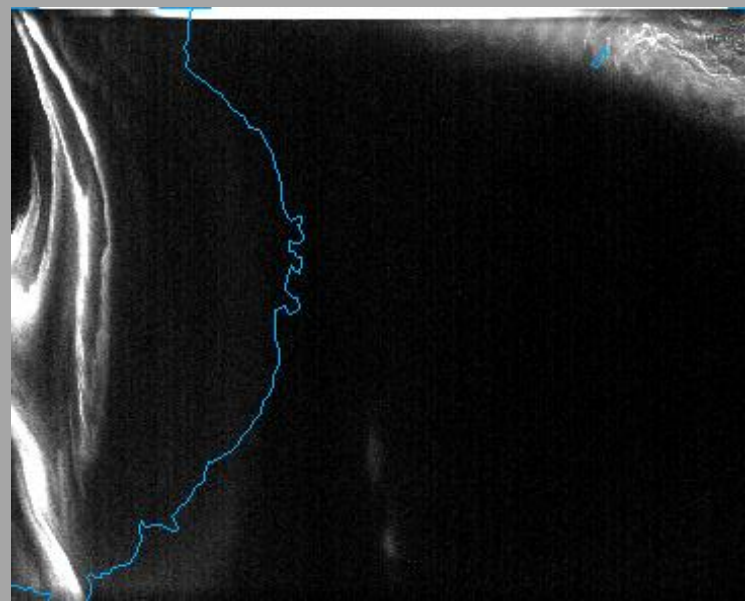
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2011-06-25 02:19:15.0



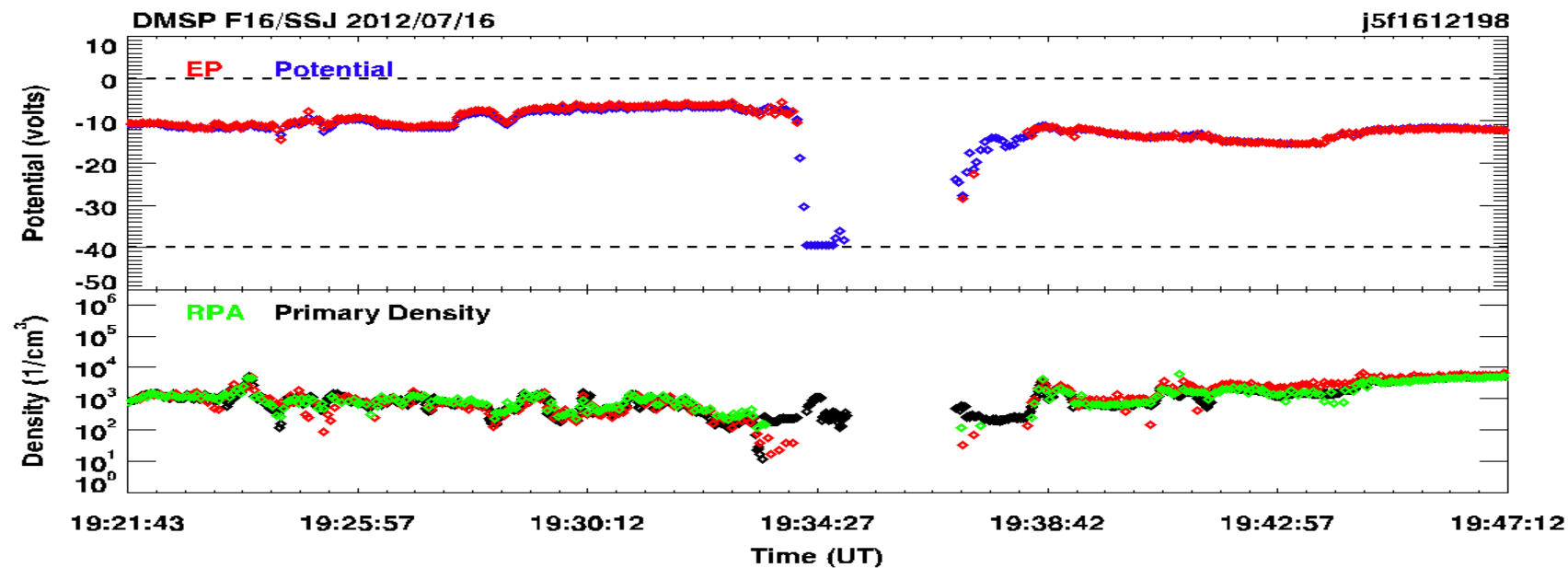
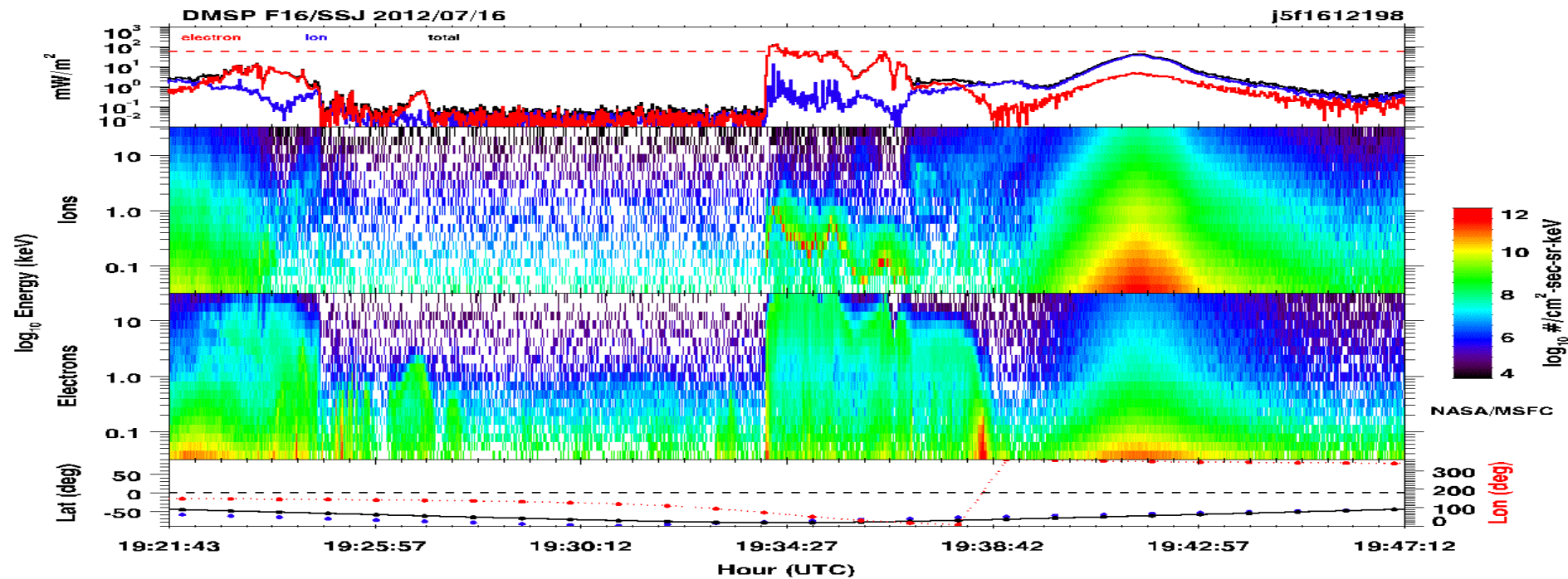


2012-07-16 19:21:43.0



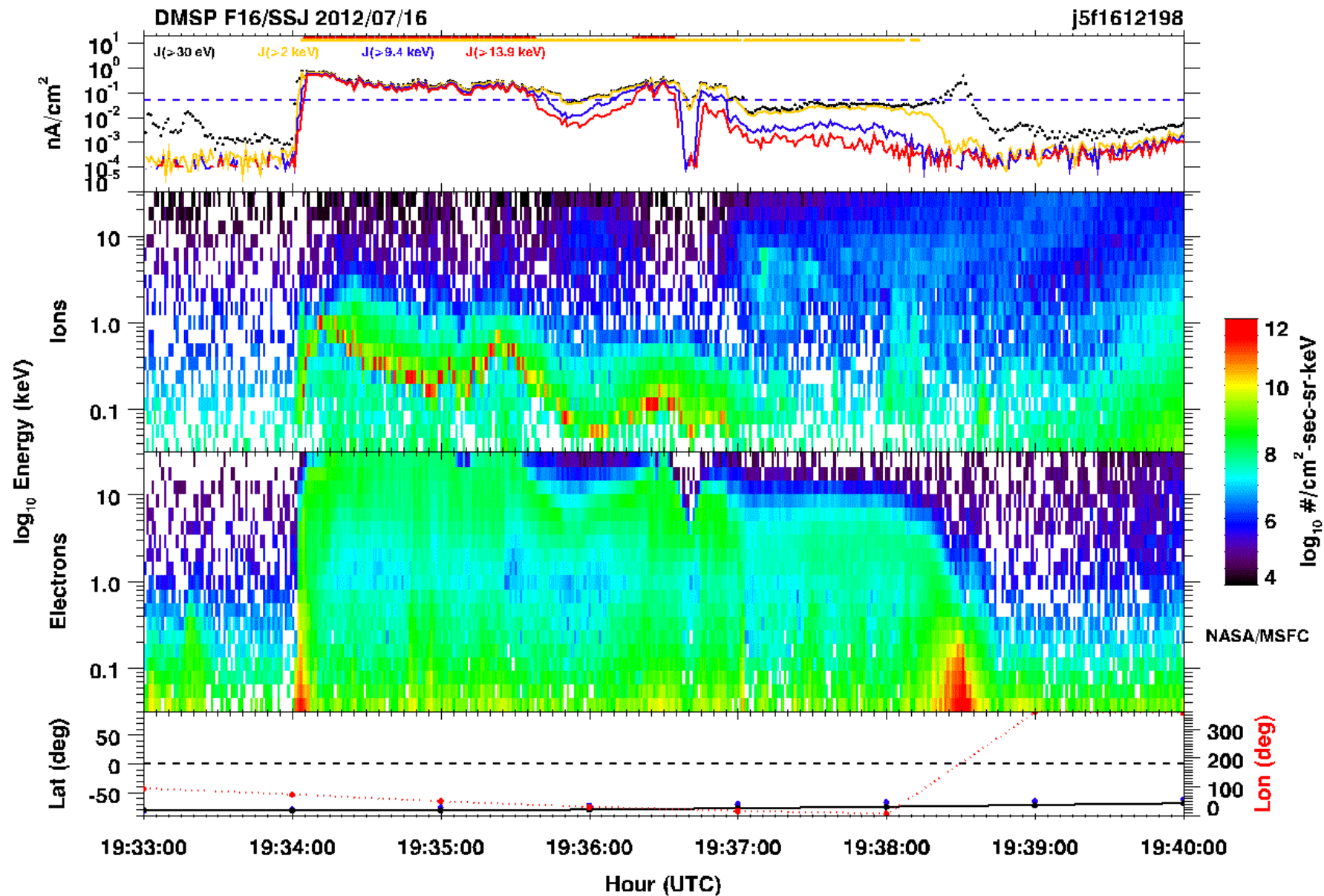
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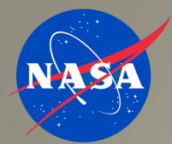
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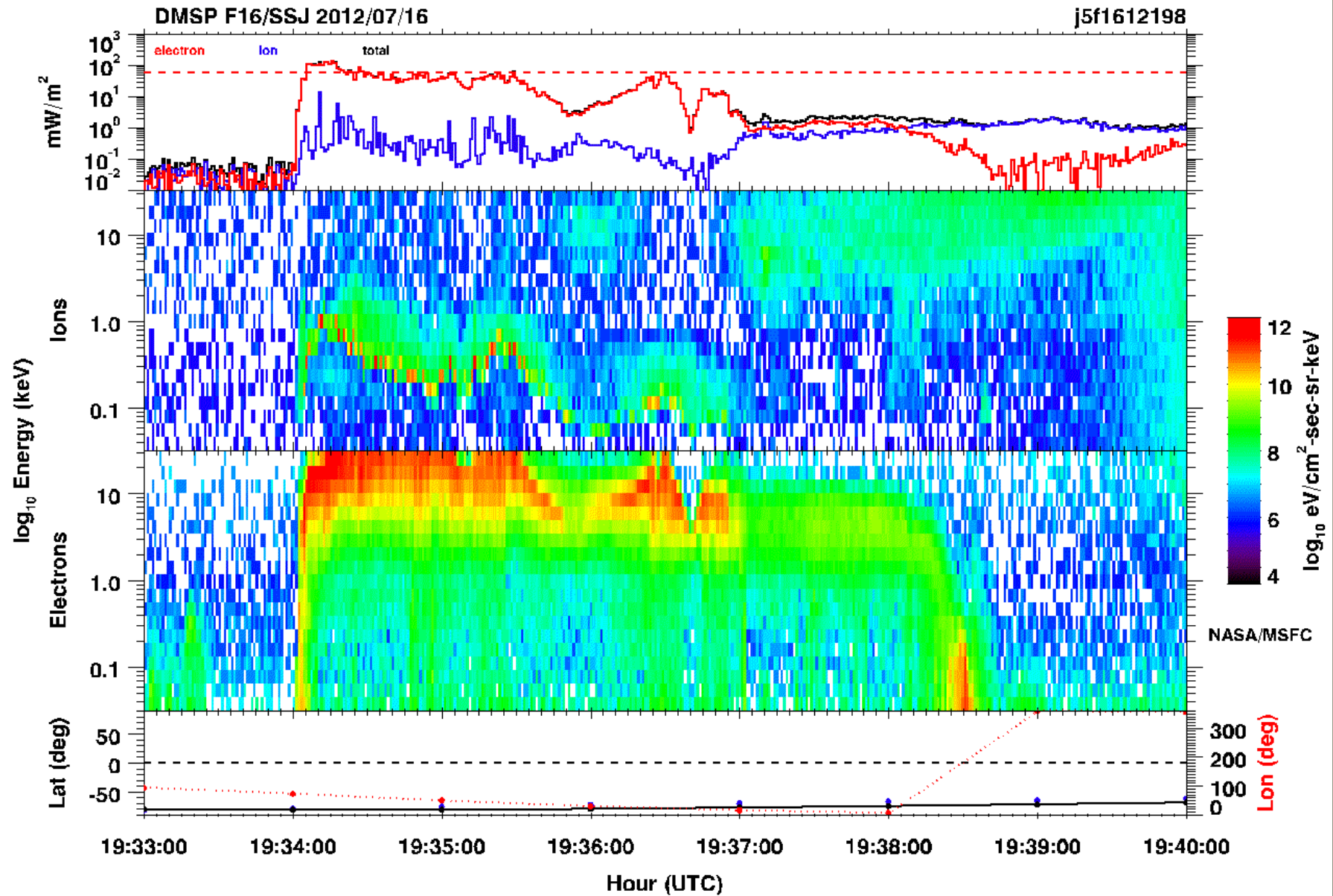


Event Detail: Number Flux and Current Density

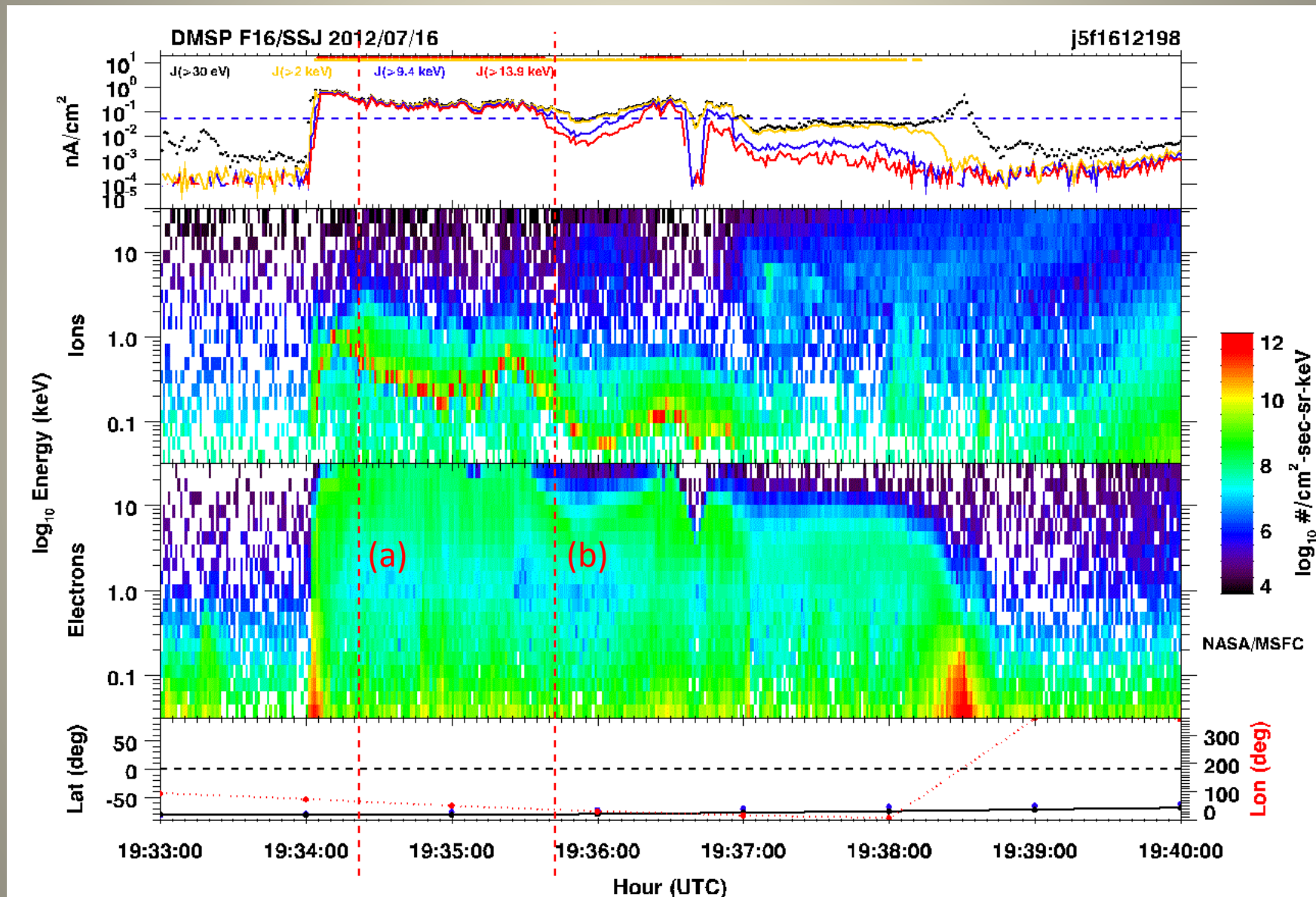


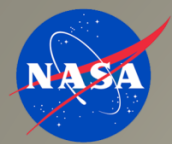


Event Detail: Energy Flux

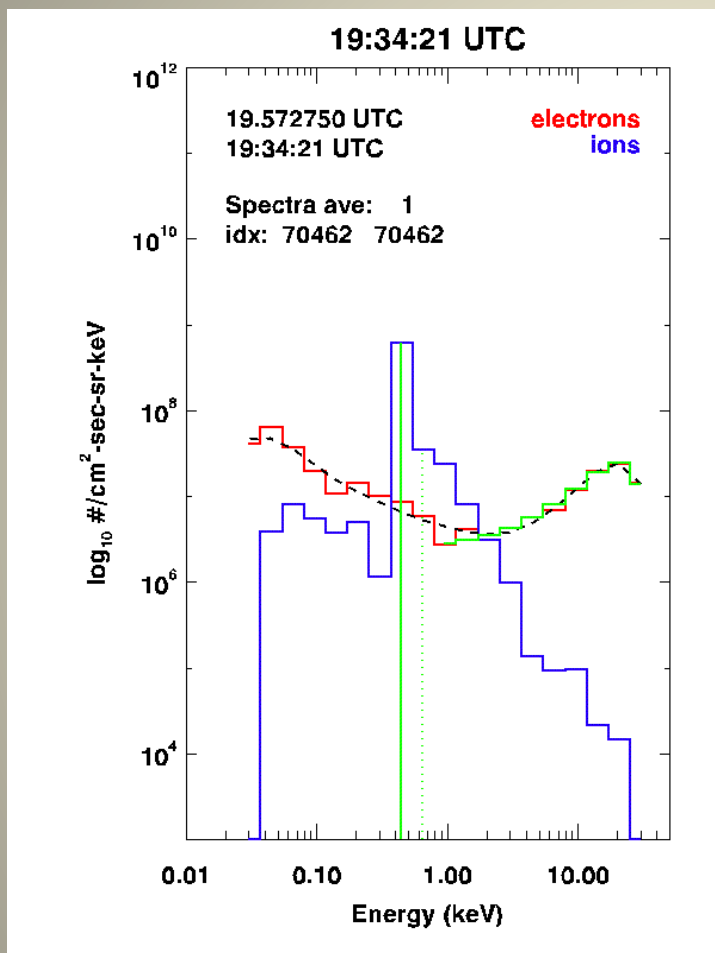


Individual Spectra

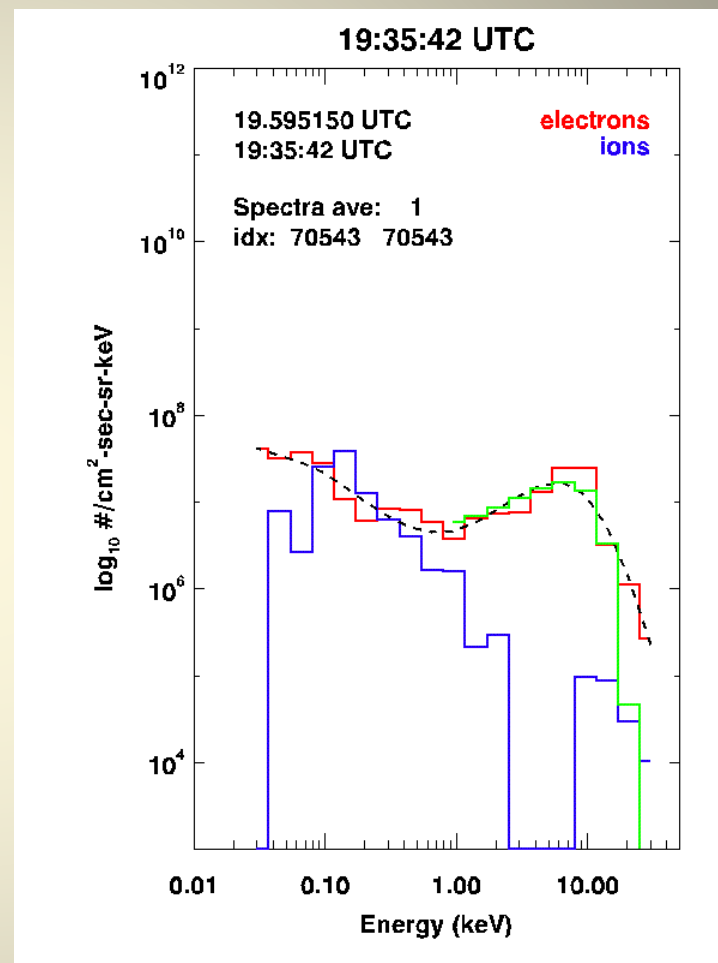




Individual Spectra



(a)



(b)



Fontheim Distribution

Ambient background

$n=4.0e12$ $1/m^3$
 $T_e=0.2$ eV

Maxwellian

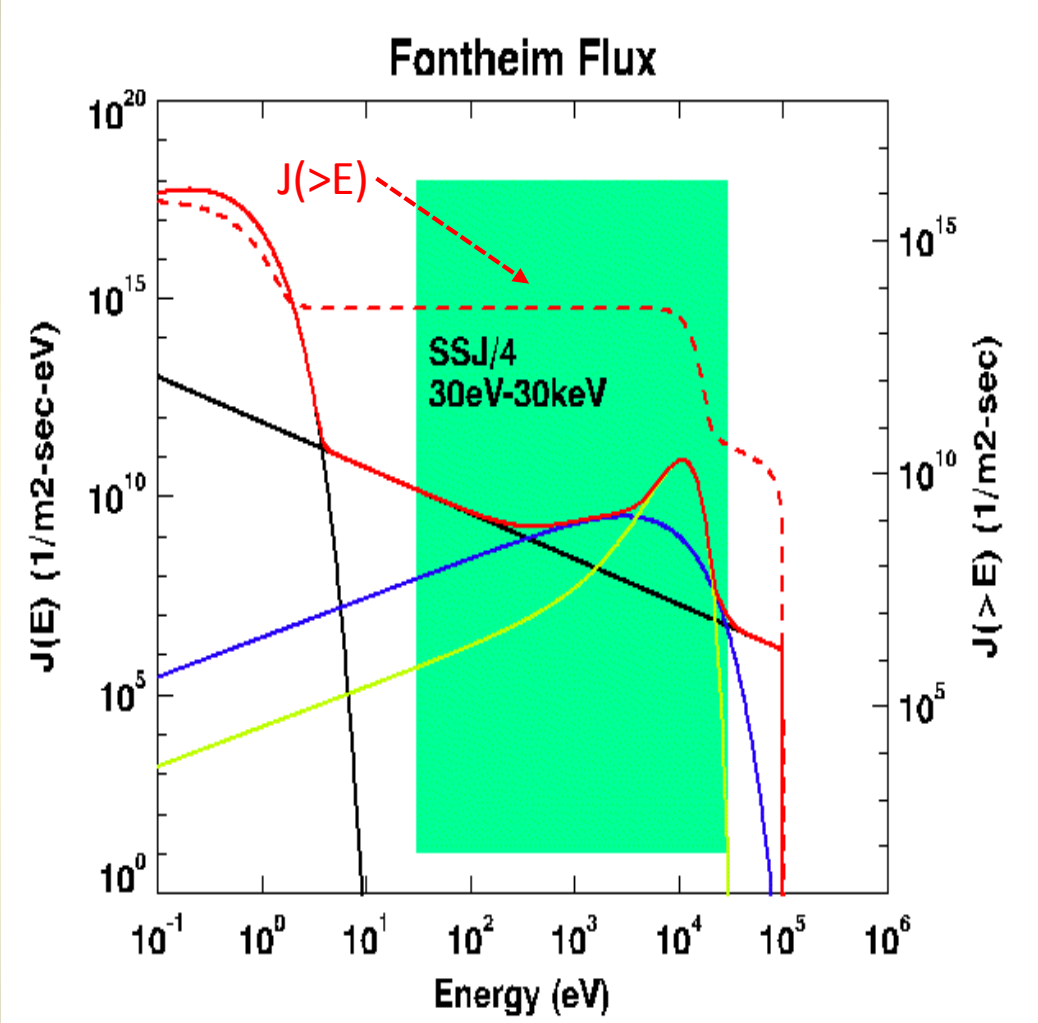
$J_{max} = 4.0e-6$ A/m^2
 $T_e = 3.0e3$ eV

Gaussian (beam)

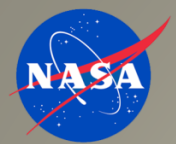
$J_{gau} = 0.9e-4$ A/m^2
 $E_{gau} = 10.0e3$ eV beam energy
 $dgau = 4.0e3$ eV beam width

Power Law

$J_{pwr} = 3.0e-7$ A/m^2
 $\alpha = 1.15$ exponent
 $E1=50.0$ eV , first energy
 $E2=1.0e5$ eV , second energy



$$\text{Flux}(E) = \sqrt{\frac{e}{2\pi\theta m_e}} \frac{E}{\theta} n \exp\left(-\frac{E}{\theta}\right) + \pi\zeta_{\max} E \exp\left(-\frac{E}{\theta_{\max}}\right) + \pi\zeta_{\text{gauss}} E \exp\left(-\left(\frac{E_{\text{gauss}} - E}{\Delta}\right)^2\right) + \pi\zeta_{\text{power}} E^{-\alpha}$$



Fontheim Distribution

Ambient background

$n=1.0e10$ $1/m^3$
 $T_e=0.2$ eV

Maxwellian

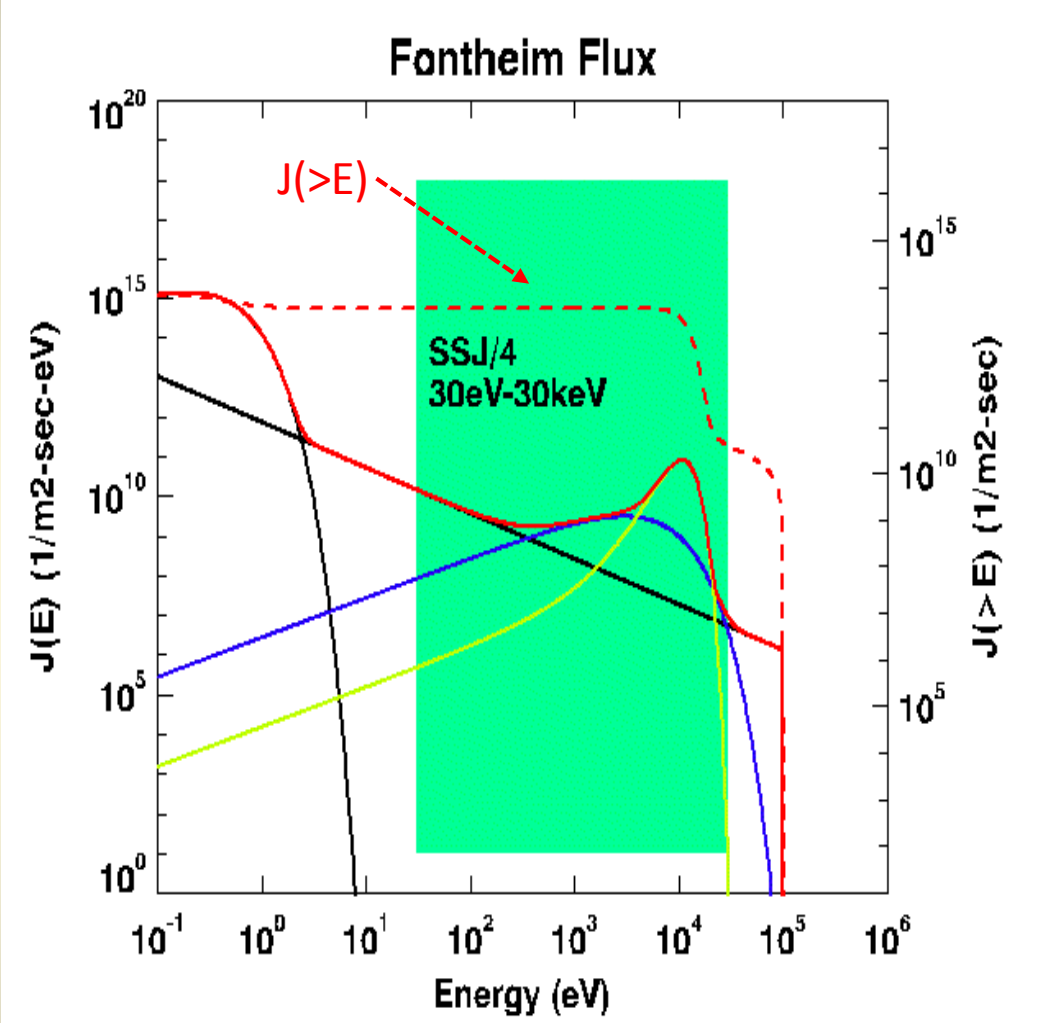
$J_{max} = 4.0e-6$ A/m^2
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Gaussian (beam)

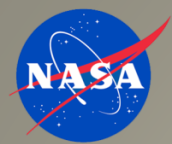
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Power Law

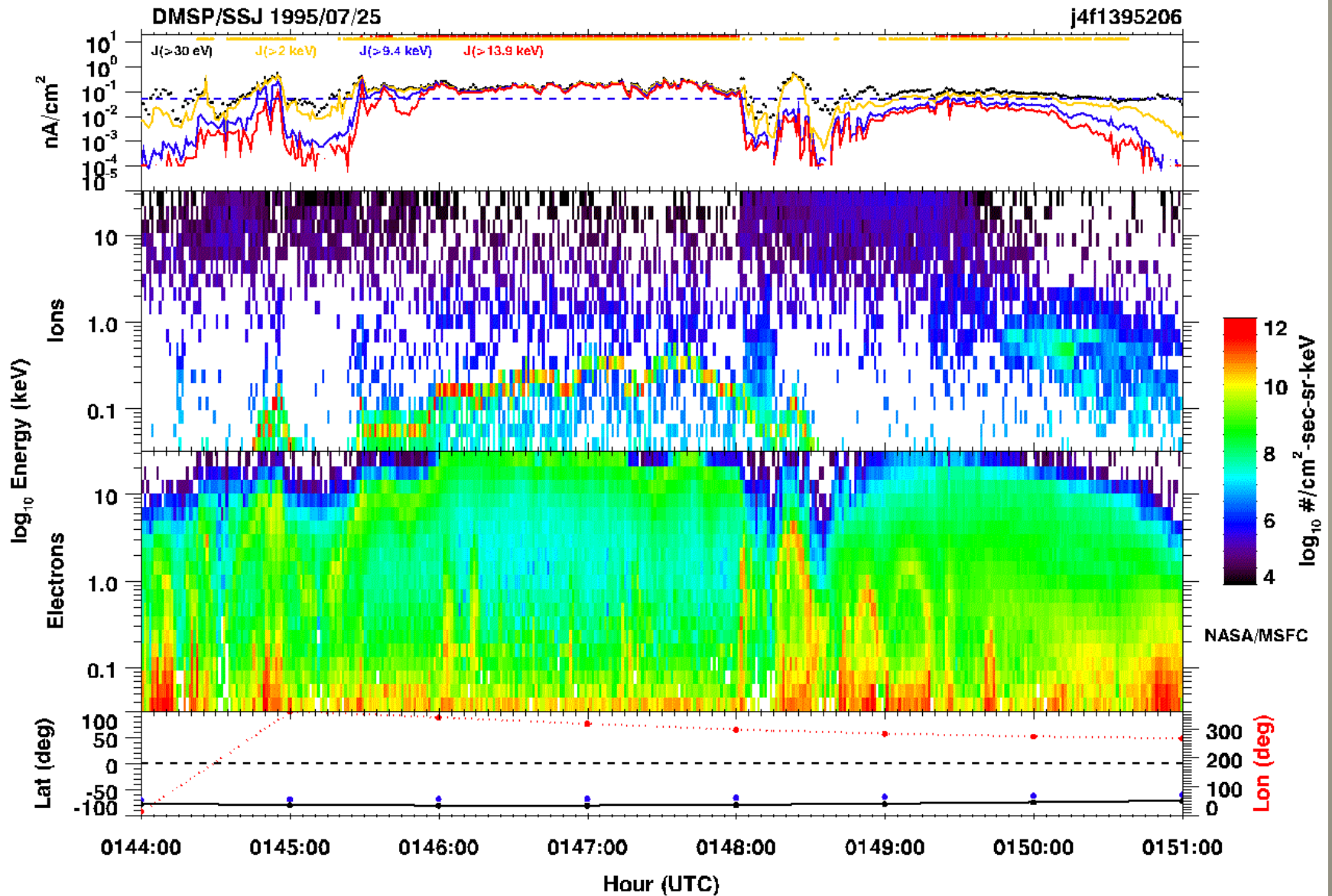
$J_{pwr} = 3.0e-7$ A/m^2
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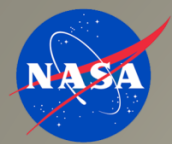


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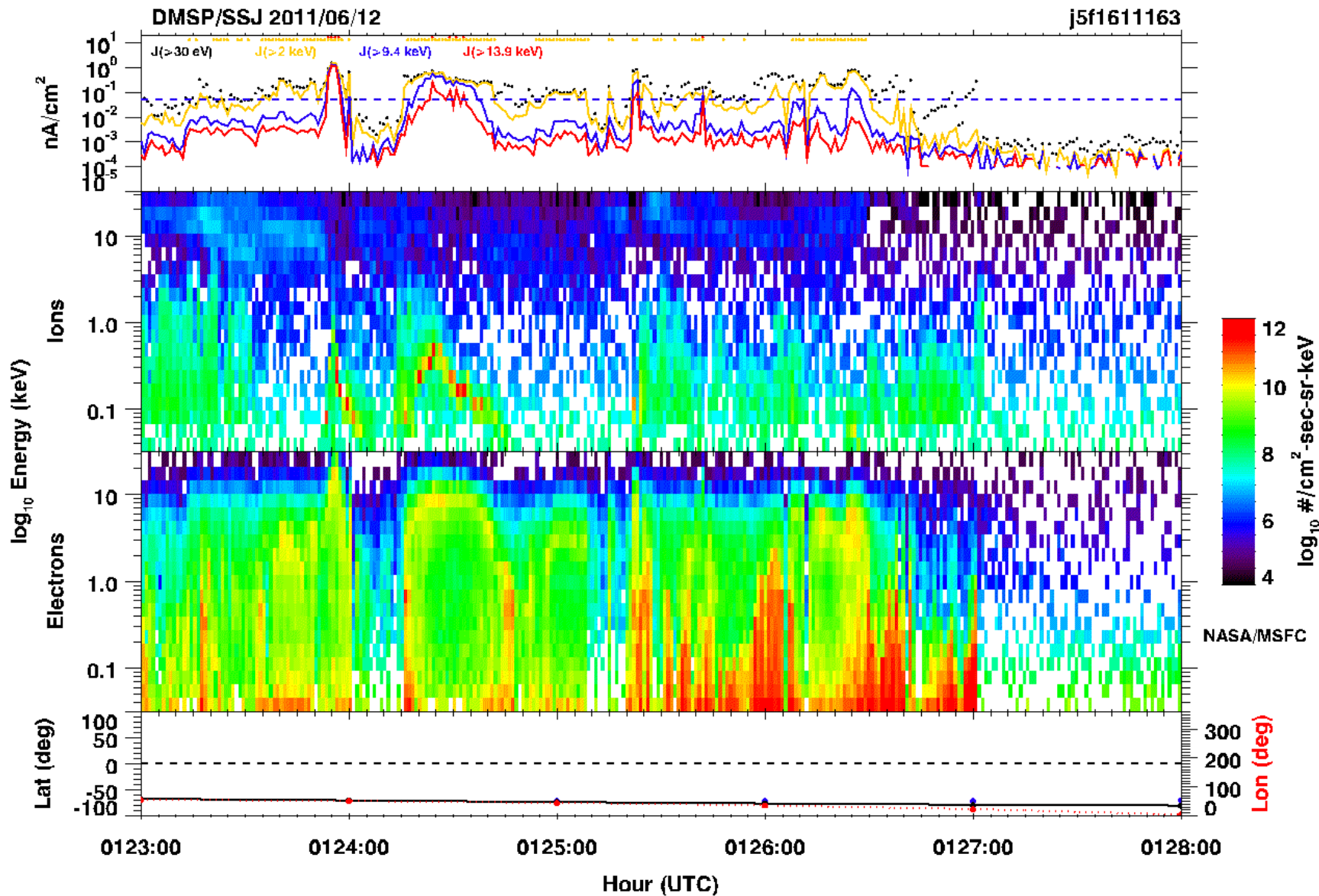


Long Duration Event



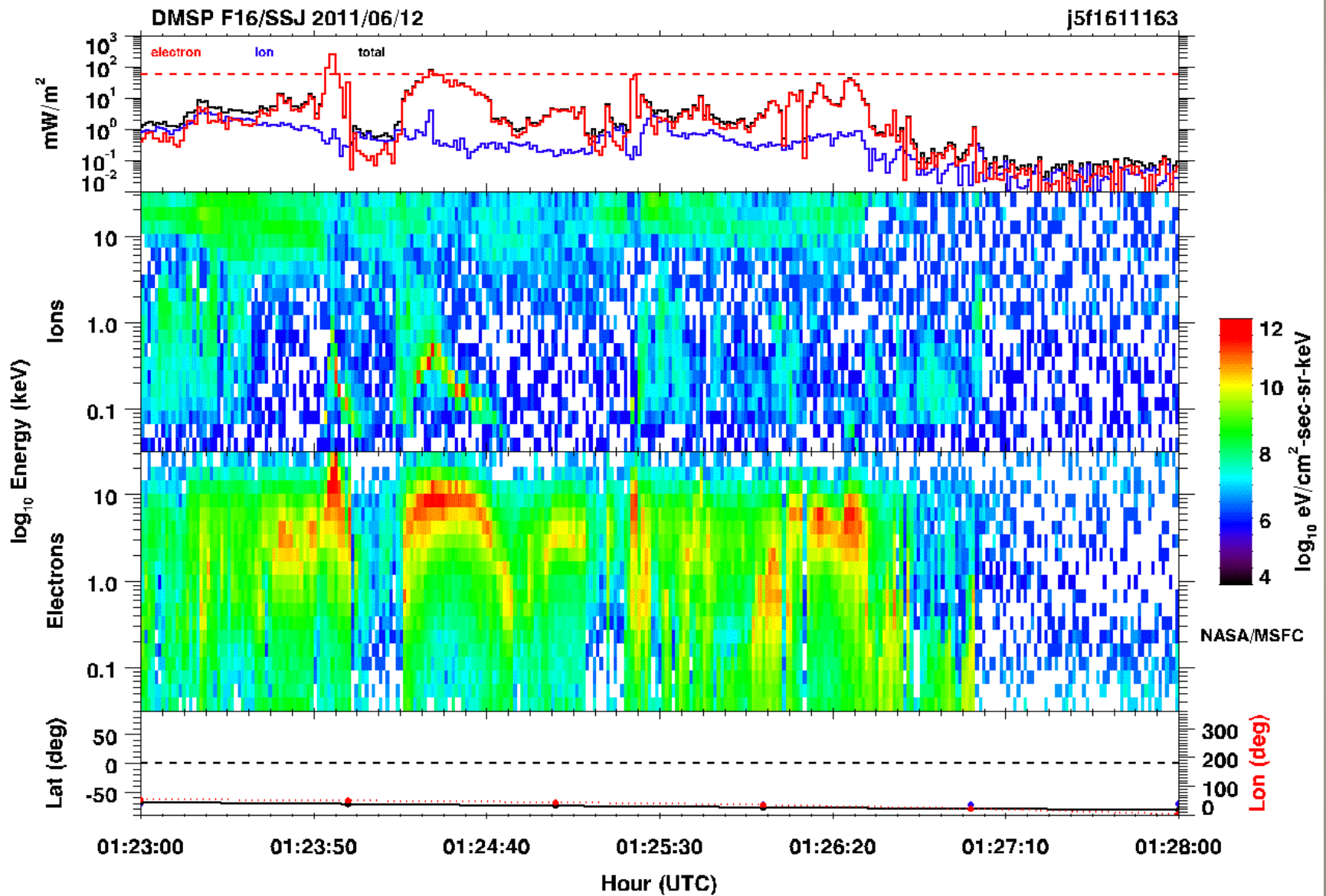


Inverted V, Broadband Aurora: N Flux





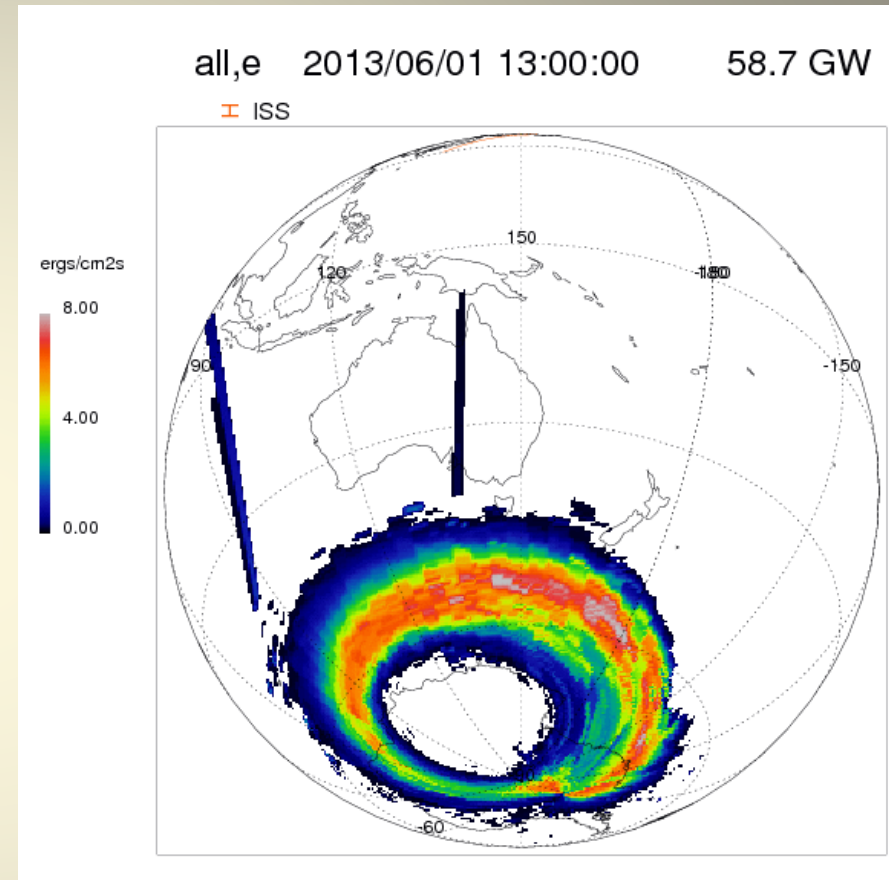
Inverted V, Broadband Aurora: E Flux





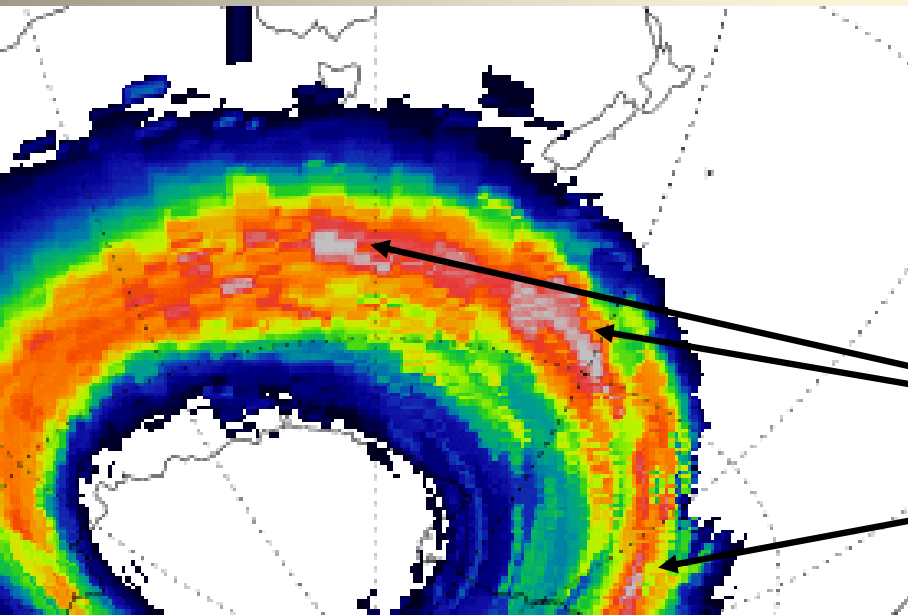
Aurora Models

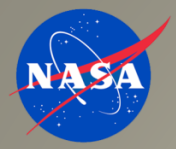
- NASA CCMC implementation of Ovation Prime is a good example of an auroral model providing total energy flux
- Total ions, electrons, and ions+electrons energy flux to 8 erg/cm²-s (=mW/m²)



NASA CCMC

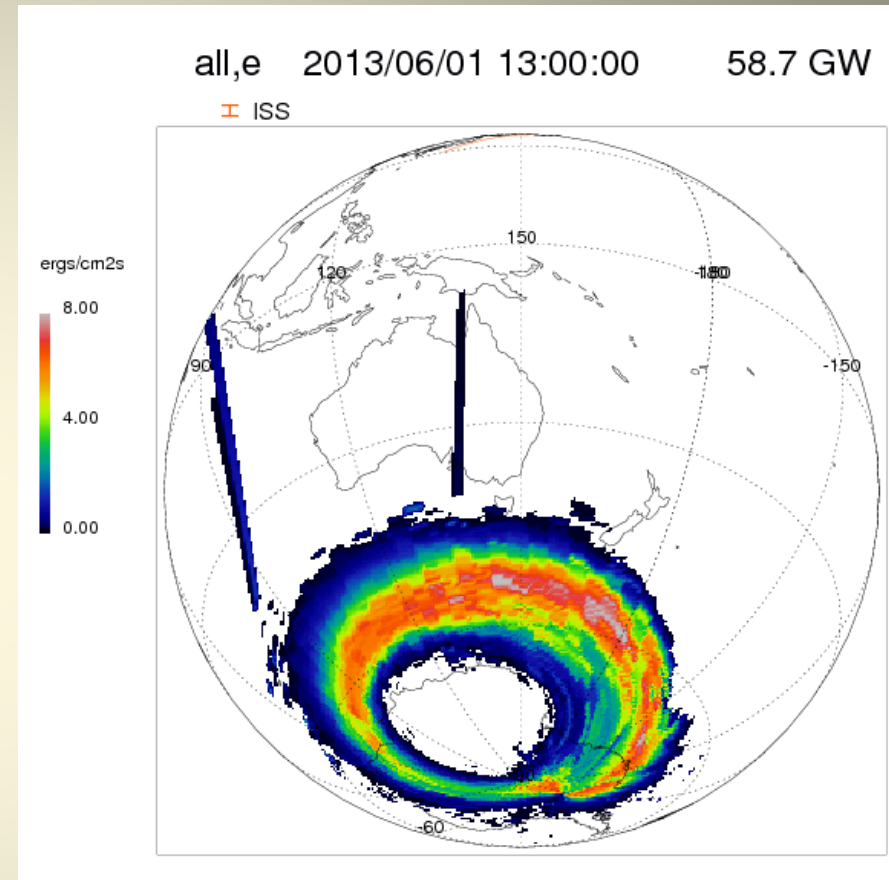
$J \geq 8 \text{ ergs/cm}^2\text{-s}$





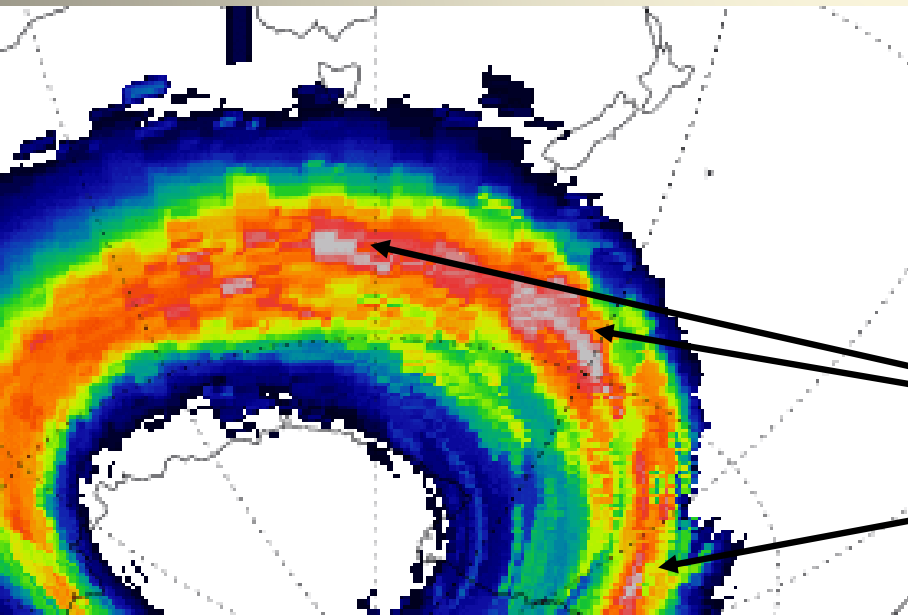
Aurora Models

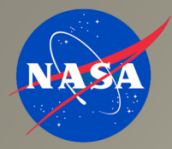
- NASA CCMC implementation of Ovation Prime is a good example of an auroral model providing total energy flux
- Total ions, electrons, and ions+electrons energy flux to 8 erg/cm²-s (=mW/m²)
- Increase the energy flux coverage to include 10's to 100's ergs/cm²-s to consider auroral charging regime?
- Energy flux for $J_E(\geq 10 \text{ keV})$ erg/cm²-s?



NASA CCMC

$J \geq 8 \text{ ergs/cm}^2\text{-s}$





Summary

- Auroral charging is a function of both the space plasma charging environment and the characteristics of the spacecraft materials
- Space weather models need to be able to predict the inverted-v electron precipitation events and background plasma density in order to characterize auroral charging environments
- Surface charging models often use the Fontheim spectrum for characterizing the charging environment.....many parameters!!
- May be adequate to predict high total energy flux or, better yet, total energy flux and energy flux for $E > \sim 10$ keV electrons



Thank You