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# Space Weather Impacts on Spacecraft Design and Operations in Auroral Charging Environments

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Spacecraft in low altitude, high inclination (including sun-synchronous) orbits are widely used for remote sensing of the Earth's land surface and oceans, monitoring weather and climate, communications, scientific studies of the upper atmosphere and ionosphere, and a variety of other scientific, commercial, and military applications. These systems are episodically exposed to environments characterized by a high flux of energetic (~1 to 10's kilovolt) electrons in regions of very low background plasma density which is similar in some ways to the space weather conditions in geostationary orbit responsible for spacecraft charging to kilovolt levels. While it is well established that charging conditions in geostationary orbit are responsible for many anomalies and even spacecraft failures, to date there have been relatively few such reports due to charging in auroral environments. This presentation first reviews the physics of the space environment and its interactions with spacecraft materials that control auroral charging rates and the anticipated maximum potentials that should be observed on spacecraft surfaces during disturbed space weather conditions. We then describe how the theoretical values compare to the observational history of extreme charging in auroral environments and discuss how space weather impacts both spacecraft design and operations for vehicles on orbital trajectories that traverse auroral charging environments.

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## Introduction

**Spacecraft in low altitude, high inclination (including sun-synchronous) orbits are widely used for remote sensing of the Earth's land surface and oceans, monitoring weather and climate, communications, scientific studies of the upper atmosphere and ionosphere, and a variety of other scientific, commercial, and military applications. These systems are episodically exposed to environments characterized by a high flux of energetic (~1 to 10's kilovolt) electrons in regions of very low background plasma density which is similar in some ways to the space weather conditions in geostationary orbit responsible for spacecraft charging to kilovolt levels. Analysis of DMSP and Freja spacecraft charging in auroral environments [*Gussenhoven et al., 1985; Yeh et al., 1987; Frooninckx and Sojka, 1992; Anderson and Koons, 1996; Wahlund et al., 1999]* have shown that three conditions are required for charging to negative potentials exceeding 100 volts:**

- **spacecraft in eclipse**
- **integral electron flux J(>10 keV) exceeds $10^8$ 1/cm$^2$-s-sr**
- **ambient ion densities less than $10^9$ to $10^{10}$ 1/m$^3$**

**These conditions assure that current collection is dominated by electrons at energies where secondary electron yields are too small to reduce the current collection and there is insufficient background plasma to balance the accumulating charging density on the spacecraft surface. Dark conditions eliminate the photoemission currents which also serve to reduce the accumulating electron surface charge density.**

**The impact of auroral charging on space missions in a number of notable cases demonstrates that following standard spacecraft charging mitigation techniques is warranted when designing systems destined for operation in auroral charging environments. Space weather is involved in the design process where it is important to know the duration, magnitude, and frequency of the most extreme auroral charging environments that must be considered for robust design.**

## Surface Charging Physics

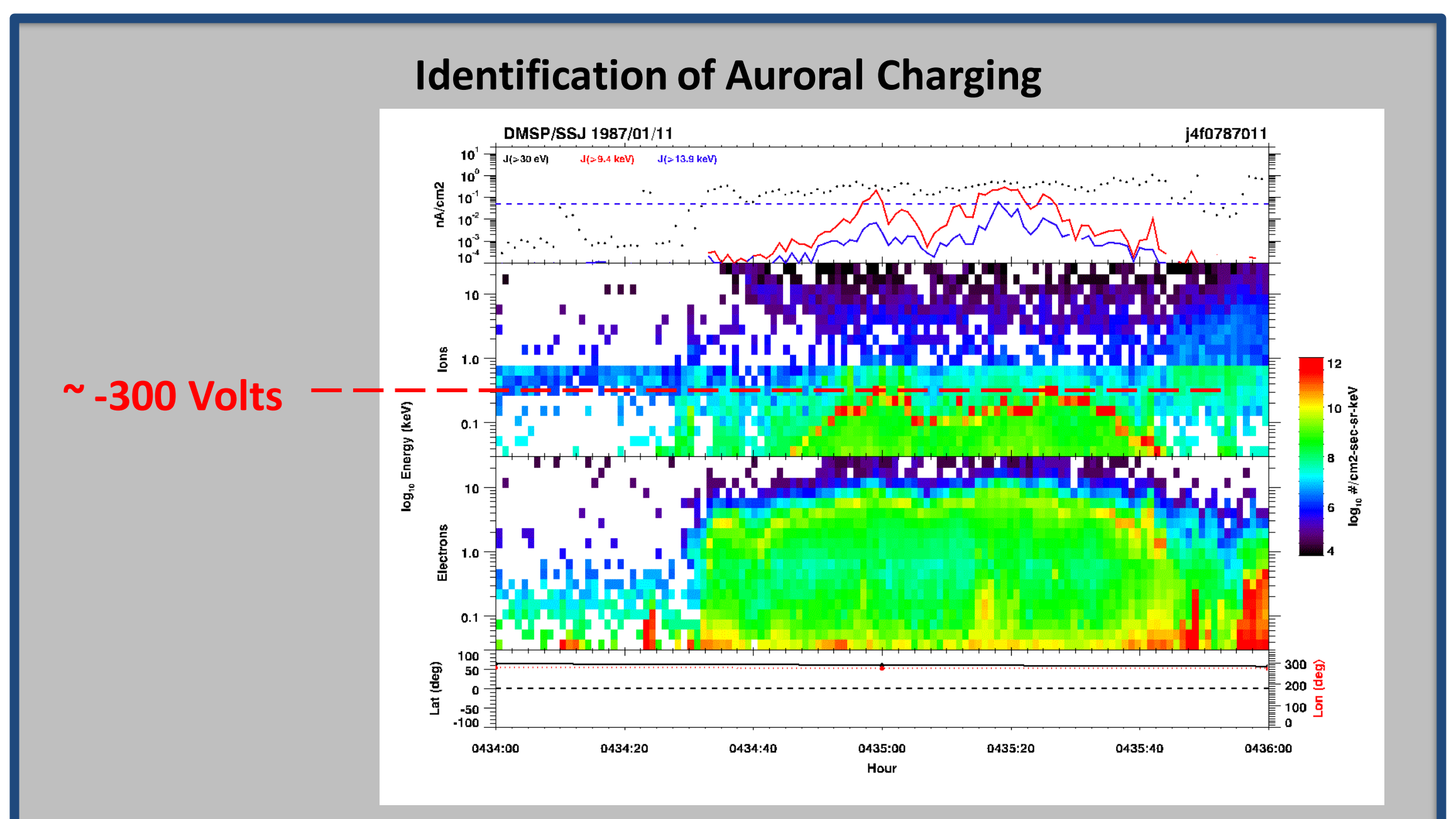
**Surface charging is the result of a current balance on the surface of a spacecraft. Charging is described by the time dependent current balance relation**

$$\frac{dQ}{dt} = \frac{d\sigma}{dt}A = C\frac{dV}{dt} = \sum_k I_k \approx 0 \text{ (at equilibrium)}$$

**where Q is the total charge and σ the surface charge accumulating on the surface area A, C is the capacitance of the area A, and V the voltage of the surface. The currents as a function of surface potential I(V) of importance to surface charging are**

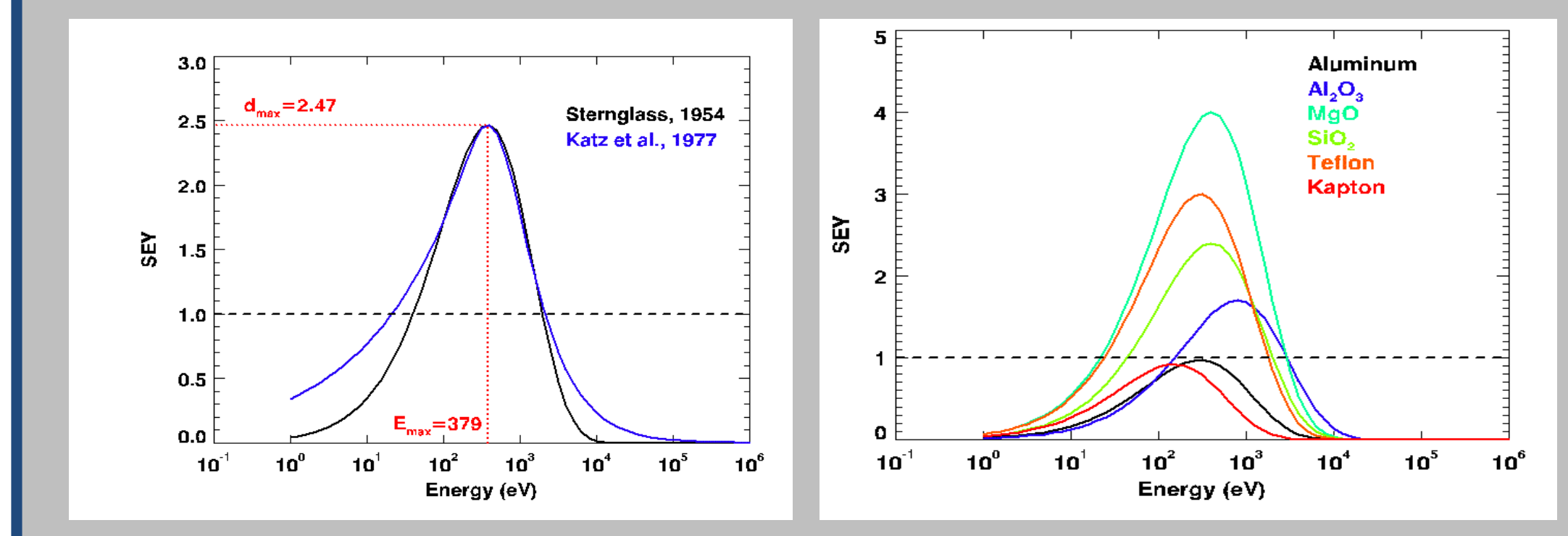
| | |
|---|---|
| $\frac{dQ}{dt} = \sum_k I_k = +I_i(V)$ | **incident ions** |
| $-I_e(V)$ | **incident electrons** |
| $+I_{bs,e}(V)$ | **backscattered electrons** |
| $+I_c(V)$ | **conduction currents** |
| $+I_{se}(V)$ | **secondary electrons due to $I_e$** |
| $+I_{si}(V)$ | **secondary electrons due to $I_i$** |
| $+I_{ph,e}(V)$ | **photoelectrons** |
| $+I_b(V)$ | **active current sources (beams, thrusters)** |

### Identification of Auroral Charging



**Auroral charging is readily identified from the "ion line" signature that appears in ion electrostatic analyzer records. Here, the ion line in the DMSP F9 satellite SSJ/4 instrument ion record is the result of ambient low energy ions accelerated by the spacecraft potential from an initial energy $E_0$ to a final energy $E = E_0 + q\phi$ where q is the charge of the ion and ϕ the spacecraft surface potential.**

### Secondary Electron Yield



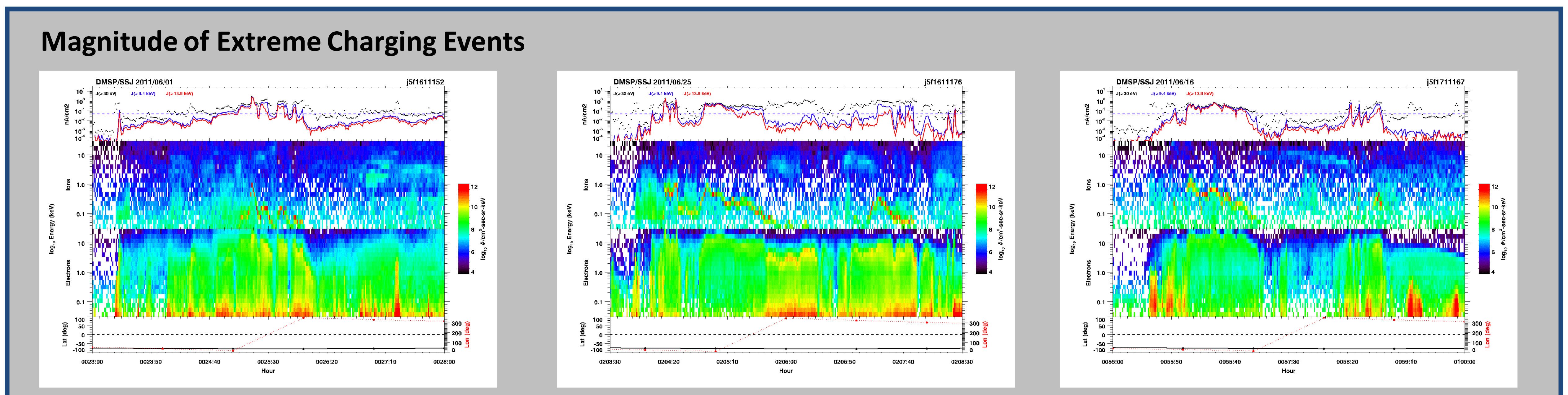
$$\delta_e(E,\theta) = \delta_{e,\max}\frac{E}{E_{\max}}\exp\left(2 - 2\sqrt{E/E_{\max}}\right)\exp[2(1-\cos\theta)]$$ ***Sternglass*, 1954**

$$\delta_e(E,\theta) = \frac{1.114\delta_{e,\max}}{\cos\theta}\left[\frac{E}{E_{\max}}\right]^{0.35}\left\{1-\exp\left[-2.28\cos\theta\left[\frac{E_{\max}}{E}\right]^{1.35}\right]\right\}$$ ***Katz et al.*, 1977**

***Whipple*, 1981**

**Low energy secondary electrons generated by impact of energetic primary electrons and ions are an important process controlling the sign and magnitude of the surface potential in auroral charging environments. Even the most intense auroral electron currents will charge spacecraft surfaces positive if the electron energies are on the order of a few kilovolts, energies where the secondary electron yields exceed unity. Electron energies on the order of ten kilovolts are required for surface charging to large negative potentials.**

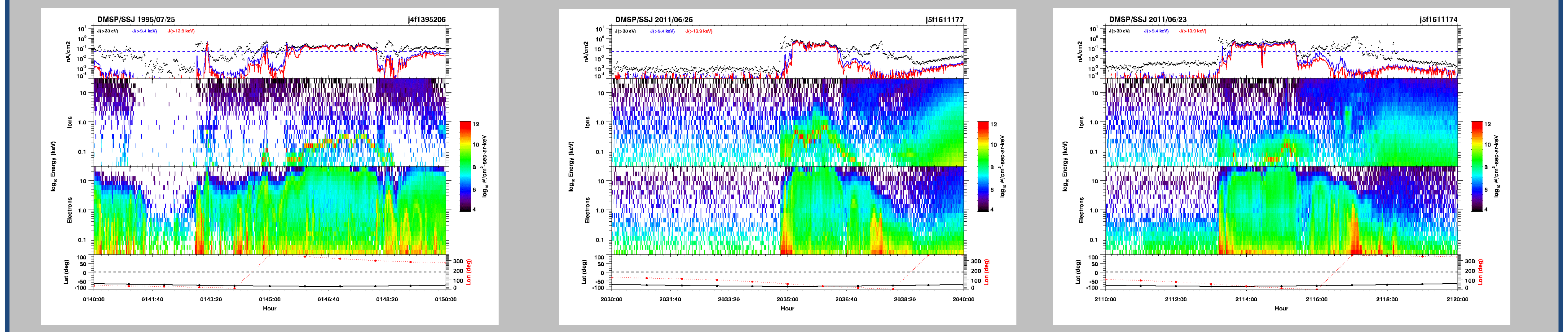
## Magnitude of Extreme Charging Events



**(a) DMSP F16 1 June 2011 |-ϕ| ~ 1000 Volts** **(b) DMSP F16 25 June 2011 |-ϕ| ~ 1000 Volts** **(c) DMSP F16 16 June 2011 |-ϕ| ~ 1400 Volts**

**Charging events exceeding a few hundred volts are a possible threat to spacecraft. An analysis of DMSP charging events by *Frooninckx and Sojka* [1992] showed charging events ranging from -46 to -1430 Volts with additional extreme events varying from -700 to -900 Volts with the most numerous and extreme events occurring during the solar minimum winter period of December 1986-January 1987. The events shown here from June 2011 are similar in magnitude to the worst case events reported by *Frooninckx and Sojka* but all occur during the ascending phase of the current solar cycle.**

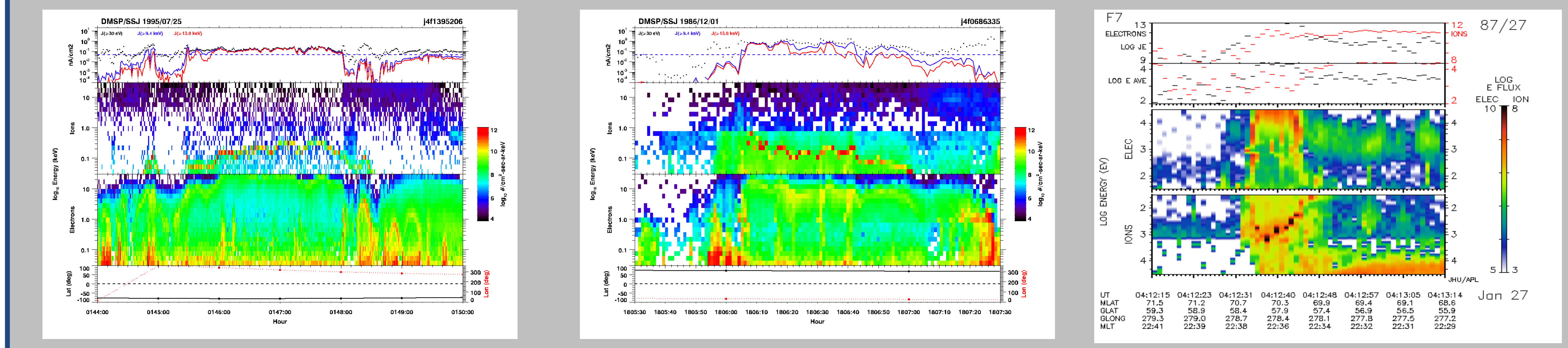
## Extreme Durations for Charging Events



**(a) DMSP F13 25 July 1995 ~3 minutes** **(b) DMSP F16 26 June 2011 ~74 seconds** **(c) DMSP F16 23 June 2011 ~58 seconds**

**Extended exposure to auroral charging conditions doesn't necessarily lead to extreme charging. Example (a) is the record duration charging event of nearly three minutes (maximum potential approximate –400 Volts) reported by *Anderson* [2001]. Events (b) and (c) are two example charging events that exceed the maximum ~60 second duration charging events reported by *Frooninckx and Sojka.* The magnitude of the maximum potential -500 Volts in (b) and -162 Volts in (c).**

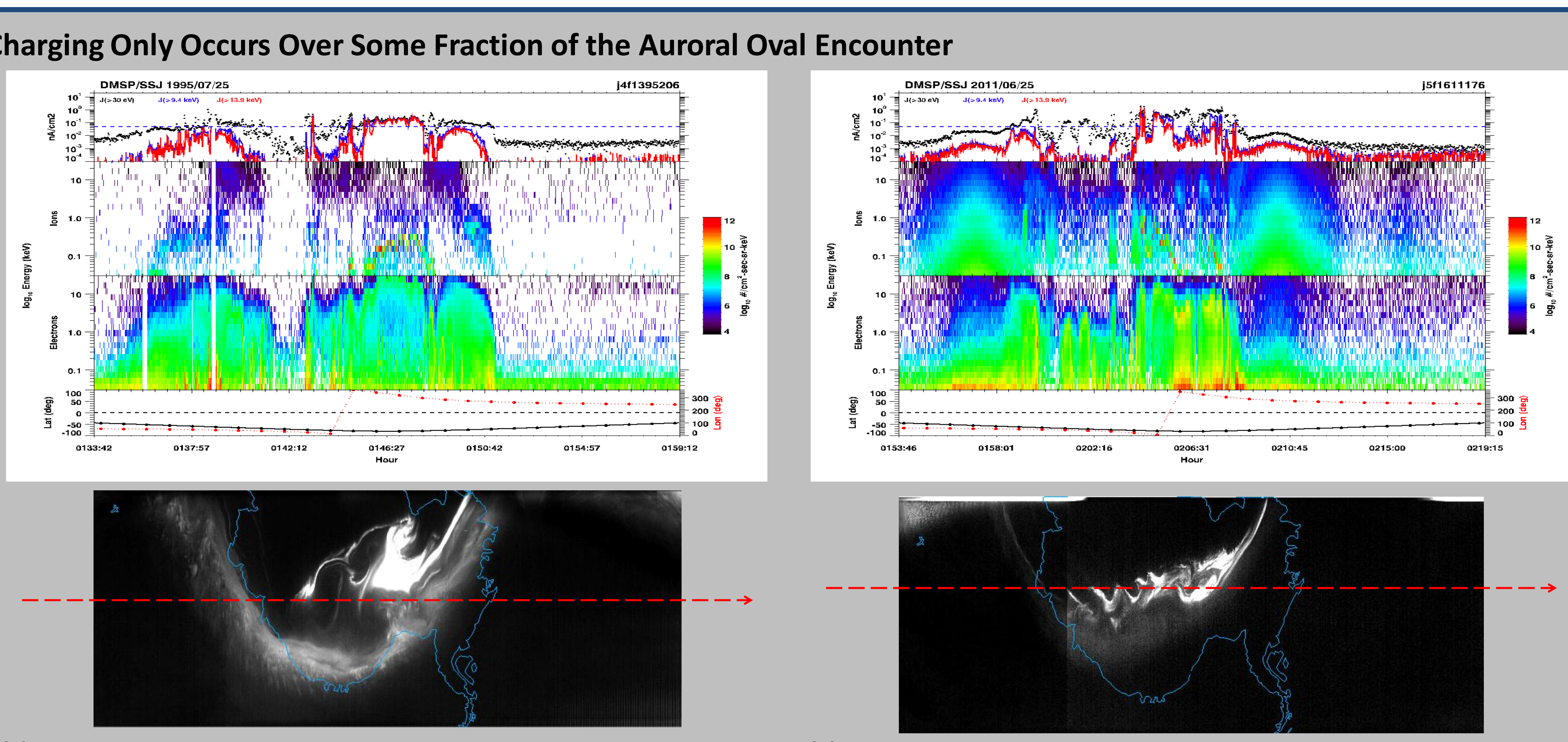
## Rise Time to Maximum Potential



**(a) DMSP F13 25 July 1995** **(b) DMSP F6 1 December 1986** **(c) DMSP F7 27 January 1987**

**The onset of frame charging is often a very rapid process requiring only a few seconds to reach the maximum potential. The temporal variations in the spacecraft potential through an individual charging event is therefore due to the variations in electron flux sampled by the spacecraft as it transits a region of auroral electron precipitation. Charging event (a) requires nearly 90 seconds to reach the maximum potential of -300 Volts and is an example of a relatively slowly developing frame potential. In contrast, (b) shows the rapid increase in spacecraft potential to –660 Volts in only four seconds. Event (c) is an increase in spacecraft potential to over -1400 Volts in approximately four seconds. This is the largest DMSP charging event reporting in the *Frooninckx and Sojka* study.**

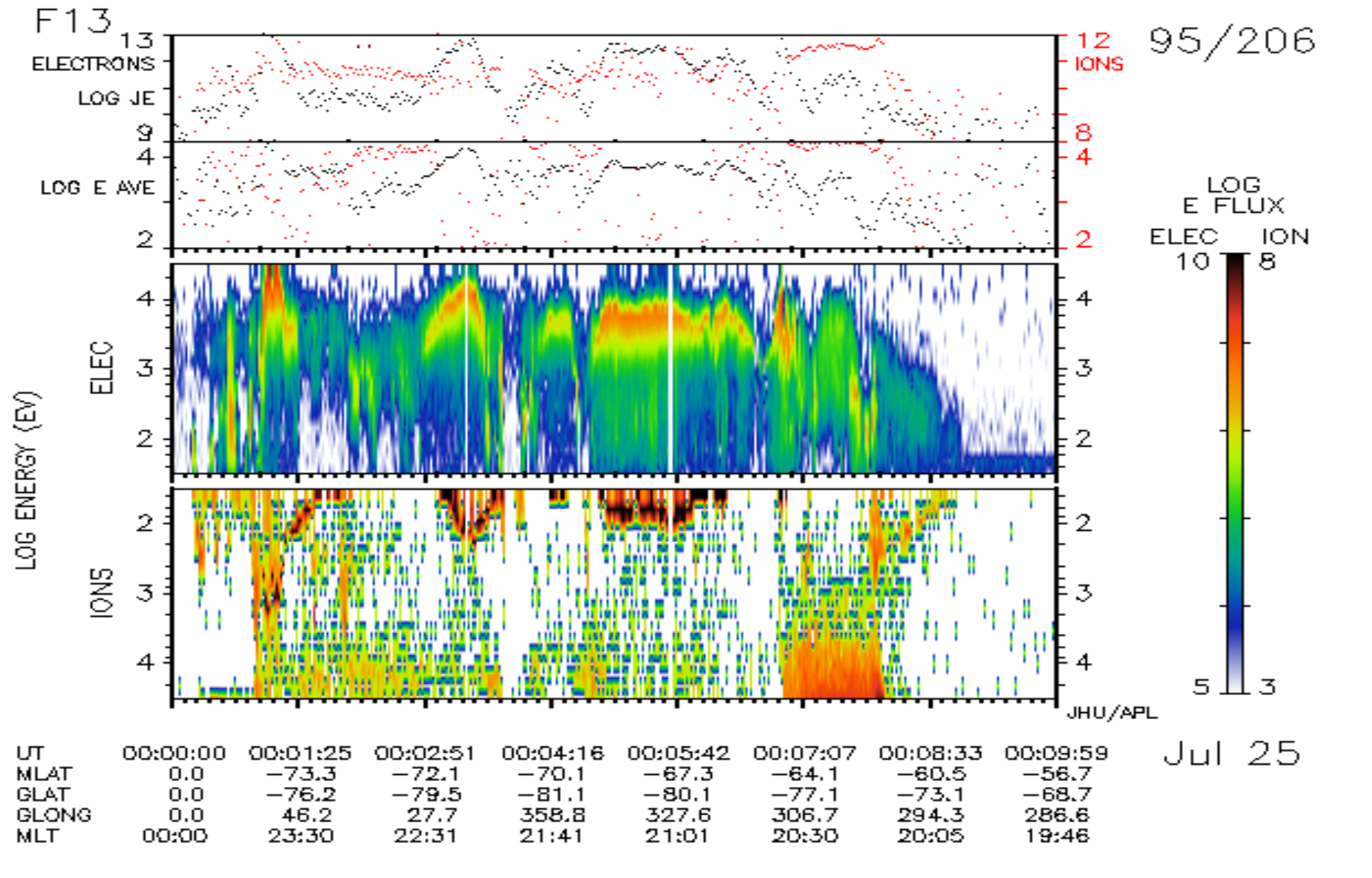
## Charging Only Occurs Over Some Fraction of the Auroral Oval Encounter



**(a)** **(b)**

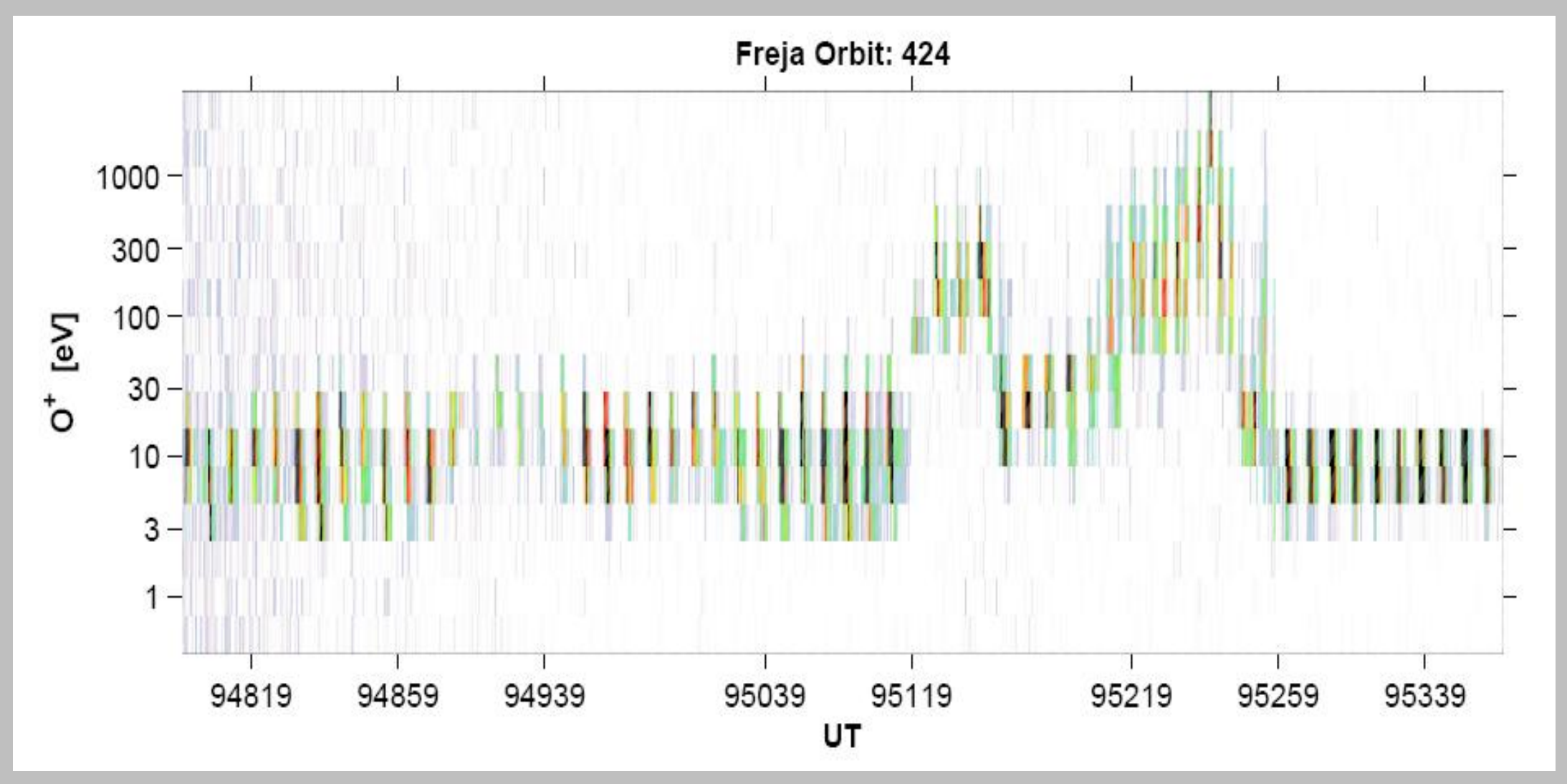
**Fortunately, auroral charging is typically limited to restricted regions within the auroral oval during active substorms. While much of the nightside oval may be generated by precipitation of electrons at kilovolt energies, these electrons are too low in energy to drive strong auroral charging due to the secondary electron yields which exceed unity for most spacecraft materials at this energy. High flux of electrons accelerated to tens of kilovolts are required for the charging events and these are typically restricted to isolated regions of the auroral oval and only last for relatively short periods of time. High inclination orbits pass through the auroral oval each orbit while spacecraft in lower inclination orbits that normally do not intersect the quiety time auroravl oval may only encounter auroral charging during strong substorms that drive the auroral equatorward to unusually low latitudes.**

## Spacecraft Exhibiting Auroral Charging



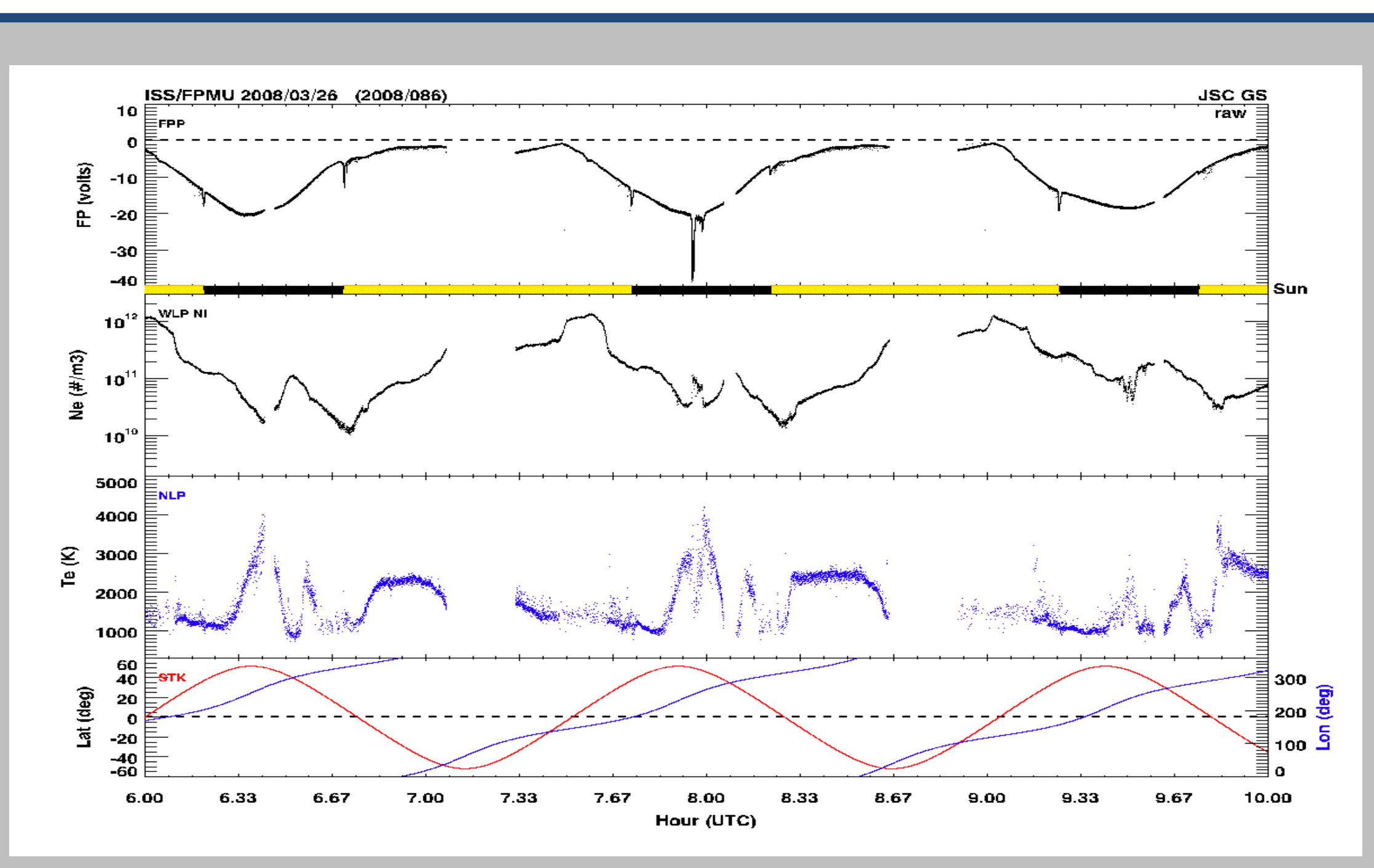
(a) DMSP 25 July 1995 multiple |-ϕ| ~ 100 Volt events

JHU/APL http://sd-www.jhuapl.edu/Aurora/



(b) Freja 7 November 1992 |-ϕ| ~ 500 Volts

Freja database: http://space.fmi.fi/spee/freja_light/Data_Tools/Freja/freja_for_spine.htm



(c) International Space Station 26 March 2008 |-ϕ| ~ 17 Volts

NASA/MSFC

All spacecraft in orbits that encounter auroral precipitation are susceptible to auroral charging, this includes all low Earth orbit satellites in sun-synchronous orbits as well as vehicles in high inclination orbits that encounter the auroral oval episodically during strong substorms. The opportunity to document charging is limited by the instrumentation on the spacecraft. (a, b) Electrostatic analyzers and (c) Langmuir probes are the most common instruments used to measure the effects of auroral charging.

## Frequency and Distribution of Auroral Charging

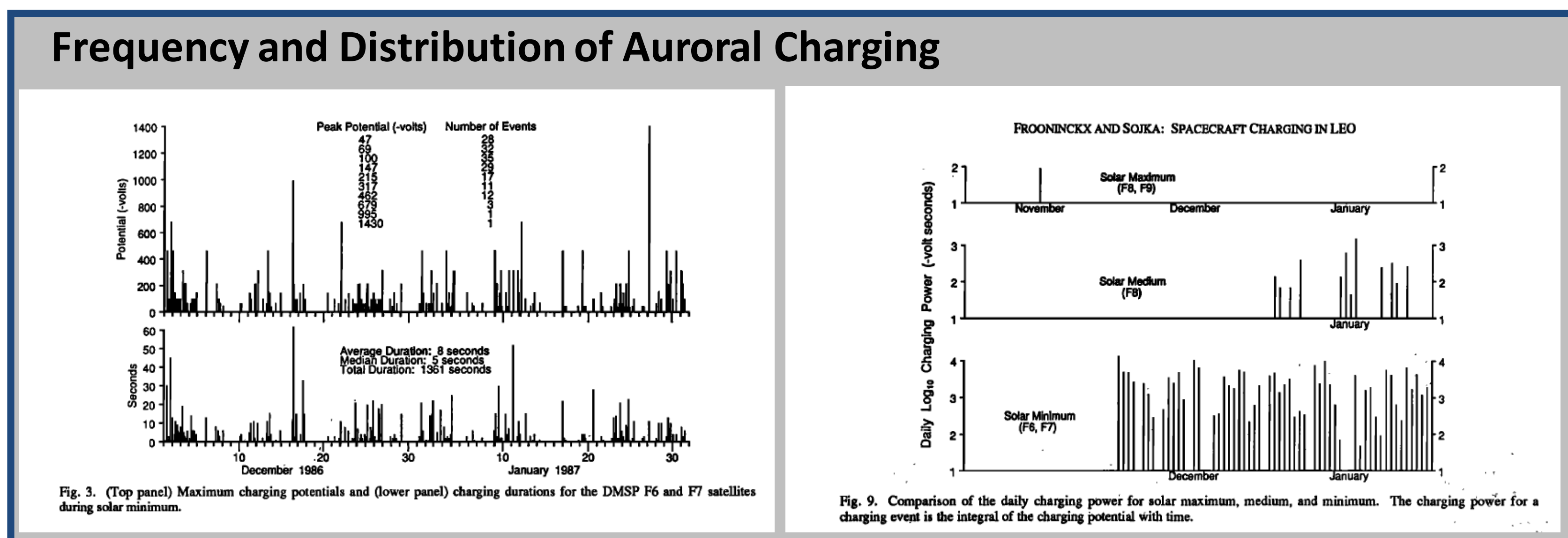
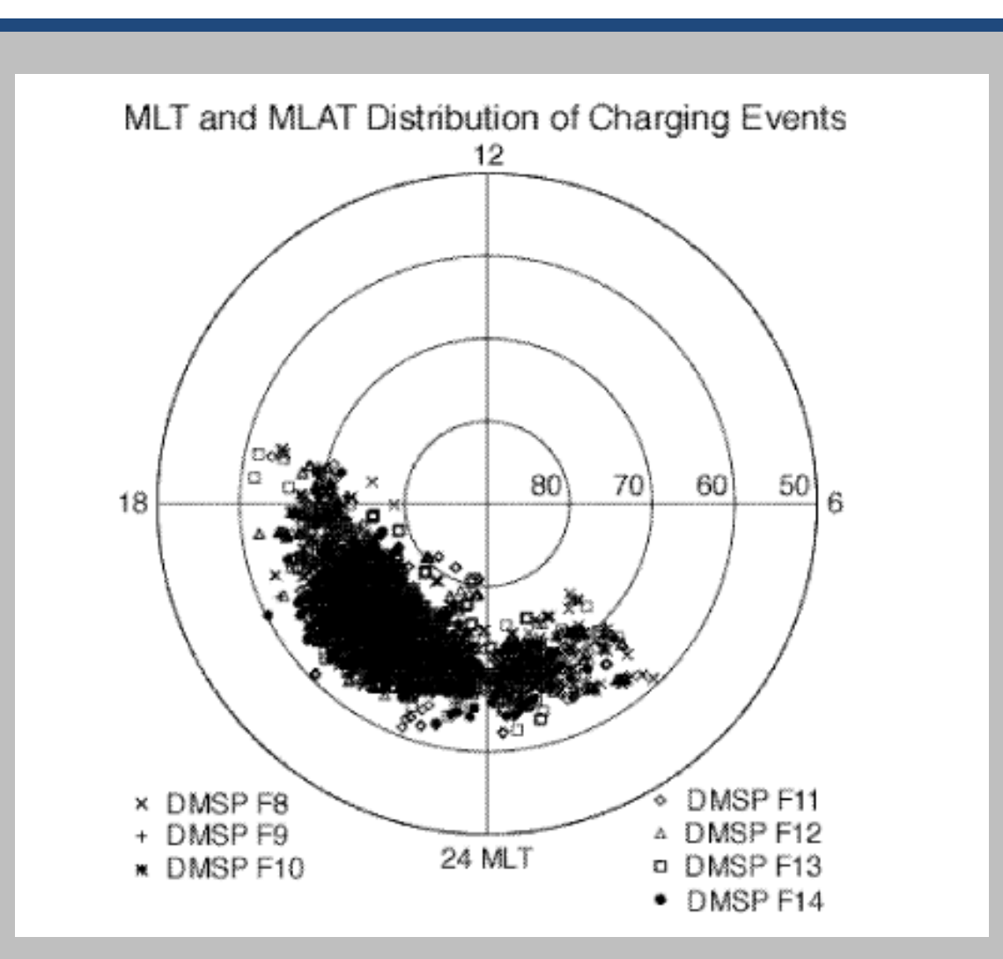


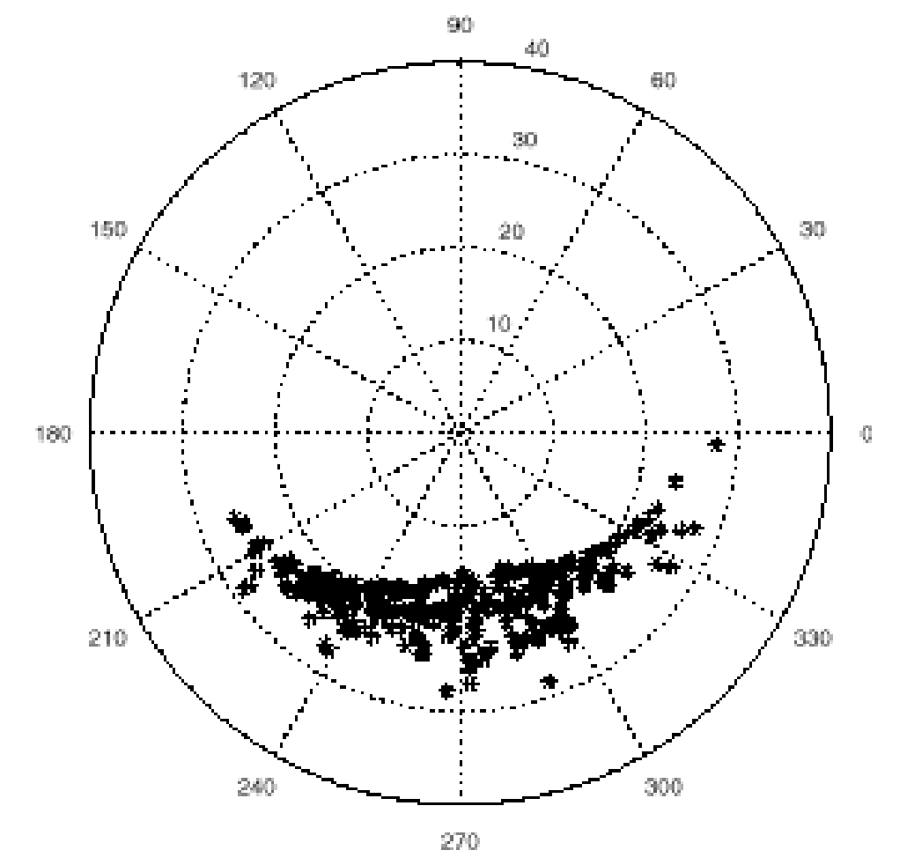
Fig. 3. (Top panel) Maximum charging potentials and (lower panel) charging durations for the DMSP F6 and F7 satellites during solar minimum.

Fig. 9. Comparison of the daily charging power for solar maximum, medium, and minimum. The charging power for a charging event is the integral of the charging potential with time.

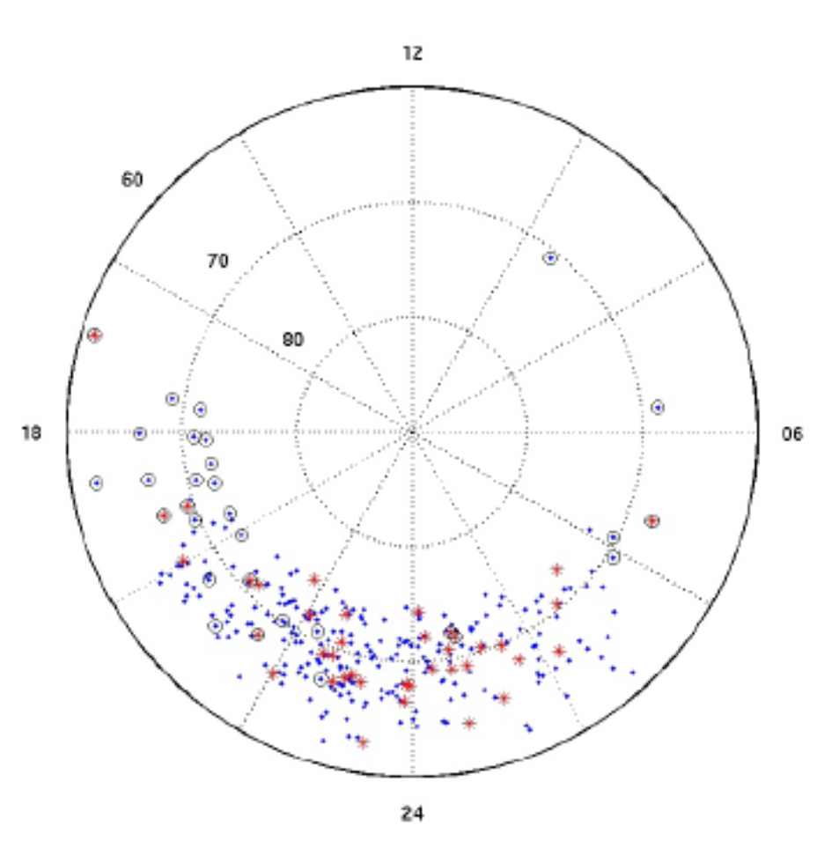
(a) DMSP Charging Frequency December 1986 – January 1987



[Anderson, 2001]



[Wahlund et al. 1999]



Blue <100 volts Red sunlight

[Ericksson and Wahlund, 2005]

(b) Distribution of DMSP and Freja Charging Events

A wealth of information on solar cycle variations and local time distributions of auroral charging events have been obtained from the DMSP and Freja spacecraft [*Frooninckx and Sojka*,1992; *Anderson* 2000,2001; Wahlund et al. 1999; Ericksson and Wahlund, 2005]. These studies show that auroral charging is most common during solar minimum and most commonly encountered in the midnight sector of the auroral oval.

## Impacts to Low Earth Orbit, Polar Missions Attributed to Energetic Electrons

| Spacecraft | Mission Impact | Reference |
|---|---|---|
| *DMSP | May, 1995, instrument anomaly | *Anderson and Koons*, 1996 |
| *ADEOS-II | 2003, loss of mission | *Nakamura*, 2005 |
| Landsat 7 | Imager artifacts | http://landsat.usgs.gov/science_an_detectorringing.php |
| Fengyun 1A | June 1988, loss of mission | *Leach and Alexander*, 1995 |
| SAMPEX | Instrument high voltage anomalies | *Mazur et al*., 2010 |
| NOAA 10 | March 1989, anomalies | *Allen*, 2000 |
| NOAA 13 | August 1993, failure | *Allen*, 2000 |

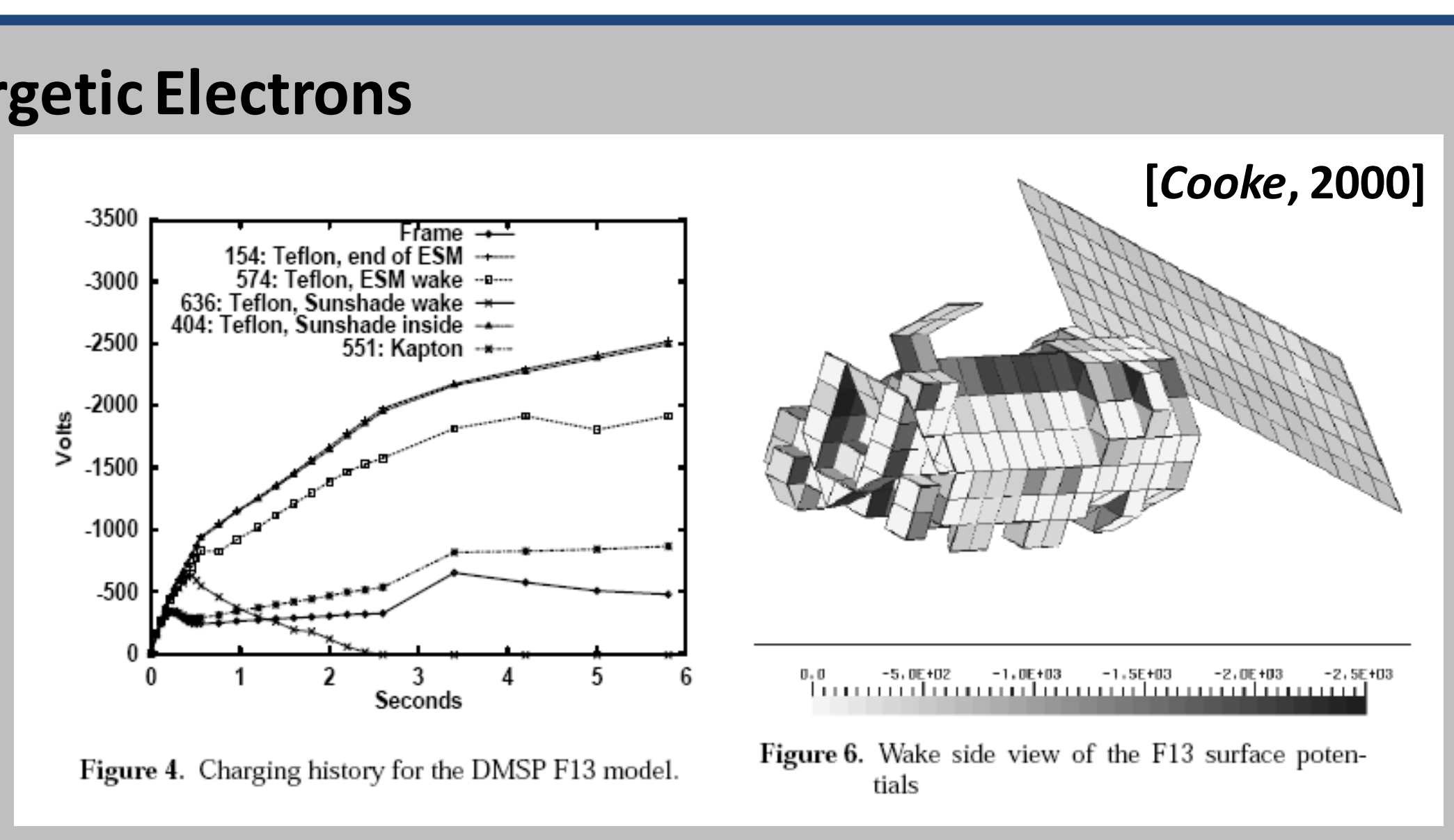
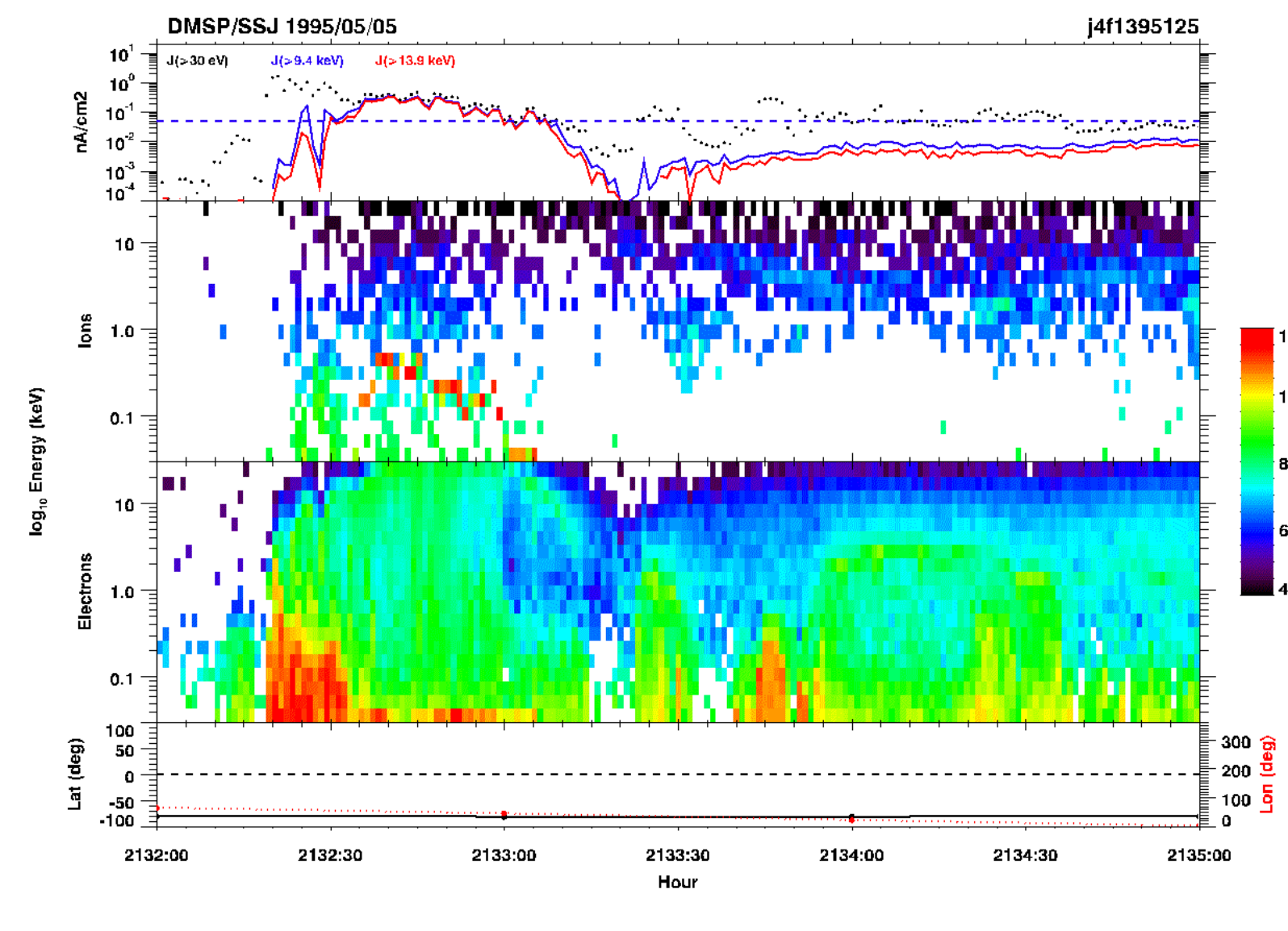


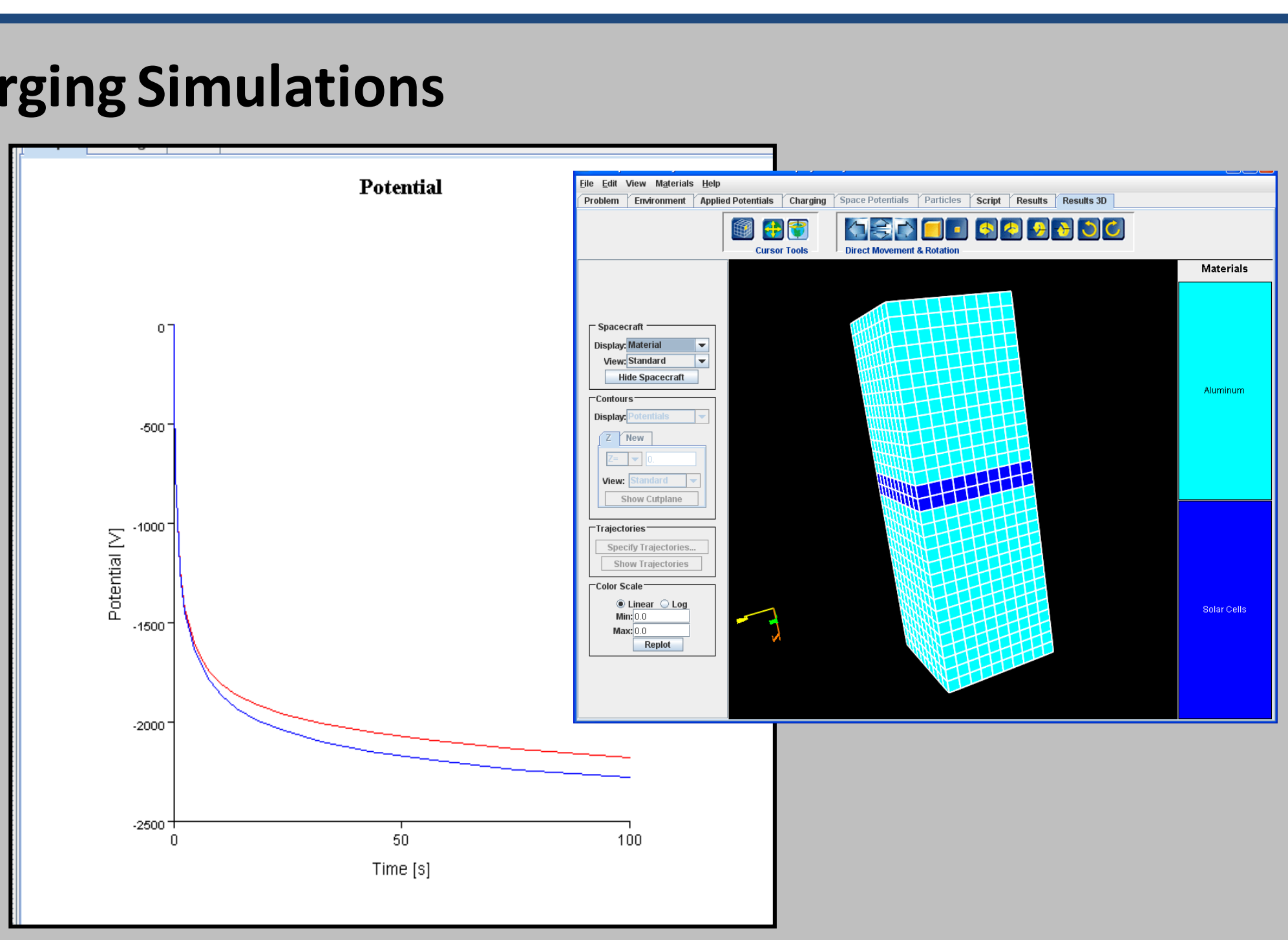
Figure 4. Charging history for the DMSP F13 model.

Figure 6. Wake side view of the F13 surface potentials

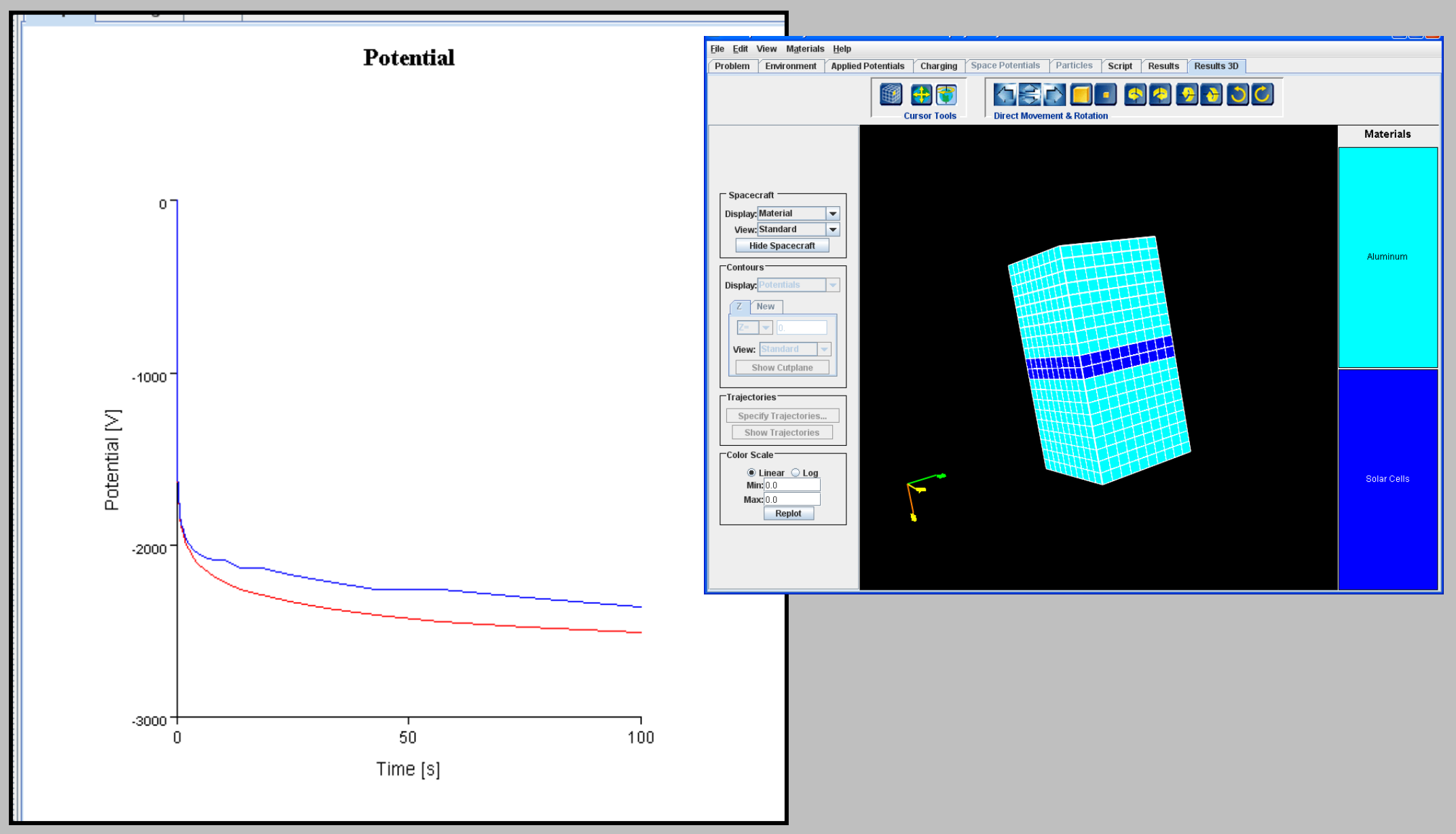


There are limited reports of anomalies or failed missions due to charging by energetic electrons in low Earth orbit. The table provides a list of instrument anomalies and spacecraft failures that have been attributed to exposure to energetic electrons. Only the DMSP and ADEOS-II events are generally considered to be related to auroral charging. The DMSP anomaly was a temporary loss of science from the Microwave Imager when the microprocessor controlling the instrument locked up at 21:32:40 UT, coincident with the maximum frame potential of -459 Volts [*Anderson and Koons*, 1996]. Surface charging simulations of the event show that while frame potentials of only -450 Volts are present, insulating surfaces develop much larger potentials leading to large differential potentials [*Cooke*, 2000]. The investigation into the ADEOS-II failure concluded that electrostatic discharge damage to the cables bringing power to the satellite from the solar arrays resulted from auroral charging as the spacecraft passed through a region of intense >30 keV auroral electrons in the northern auroral region [*Nakamura*, 2010].

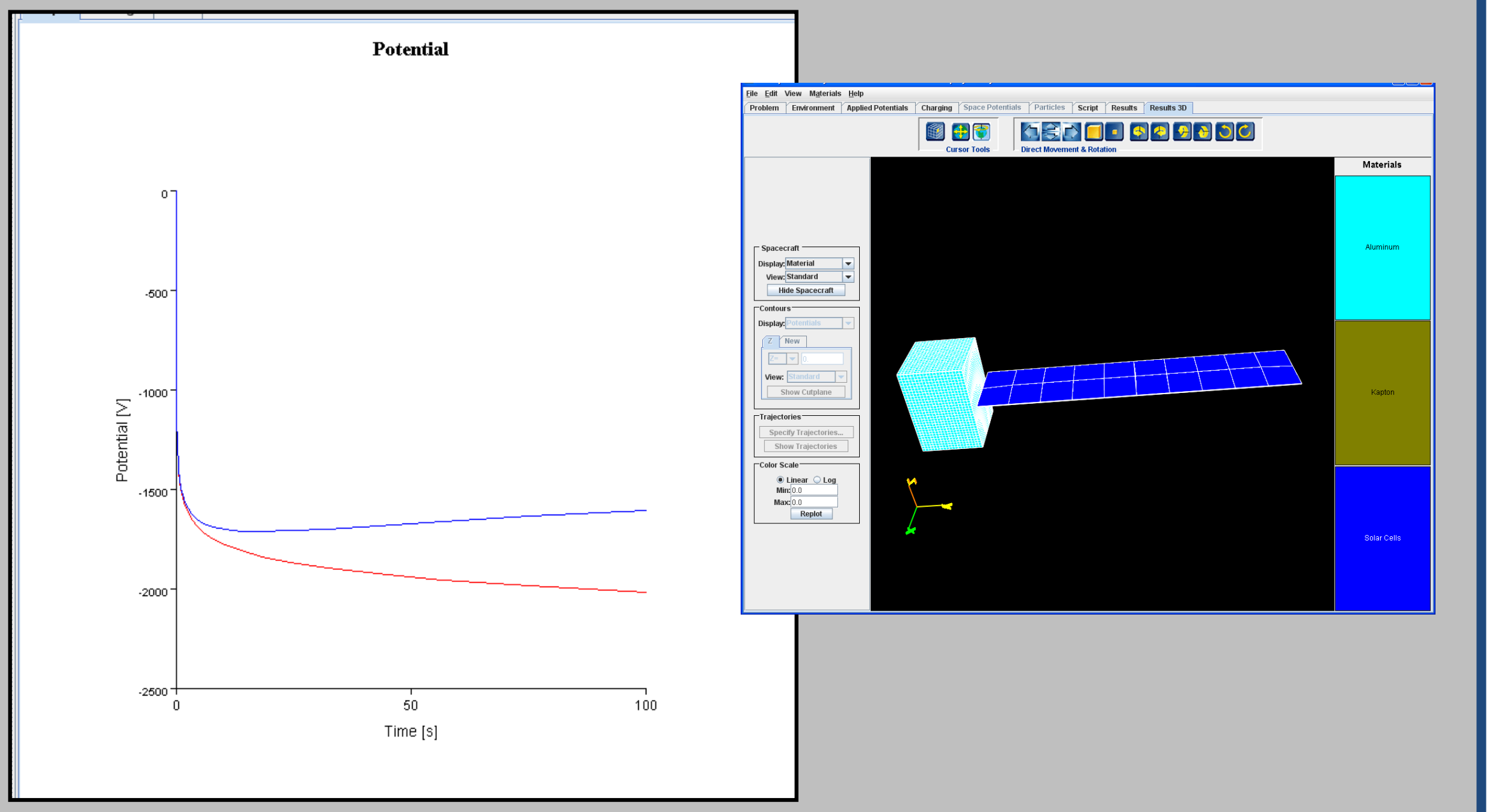
## Charging Simulations



(a) 50 cm x 50 cm x 150 cm in darkness
solar cells on aluminum



(b) 1 m x 1 m x 2 m in darkness
solar cells on aluminum

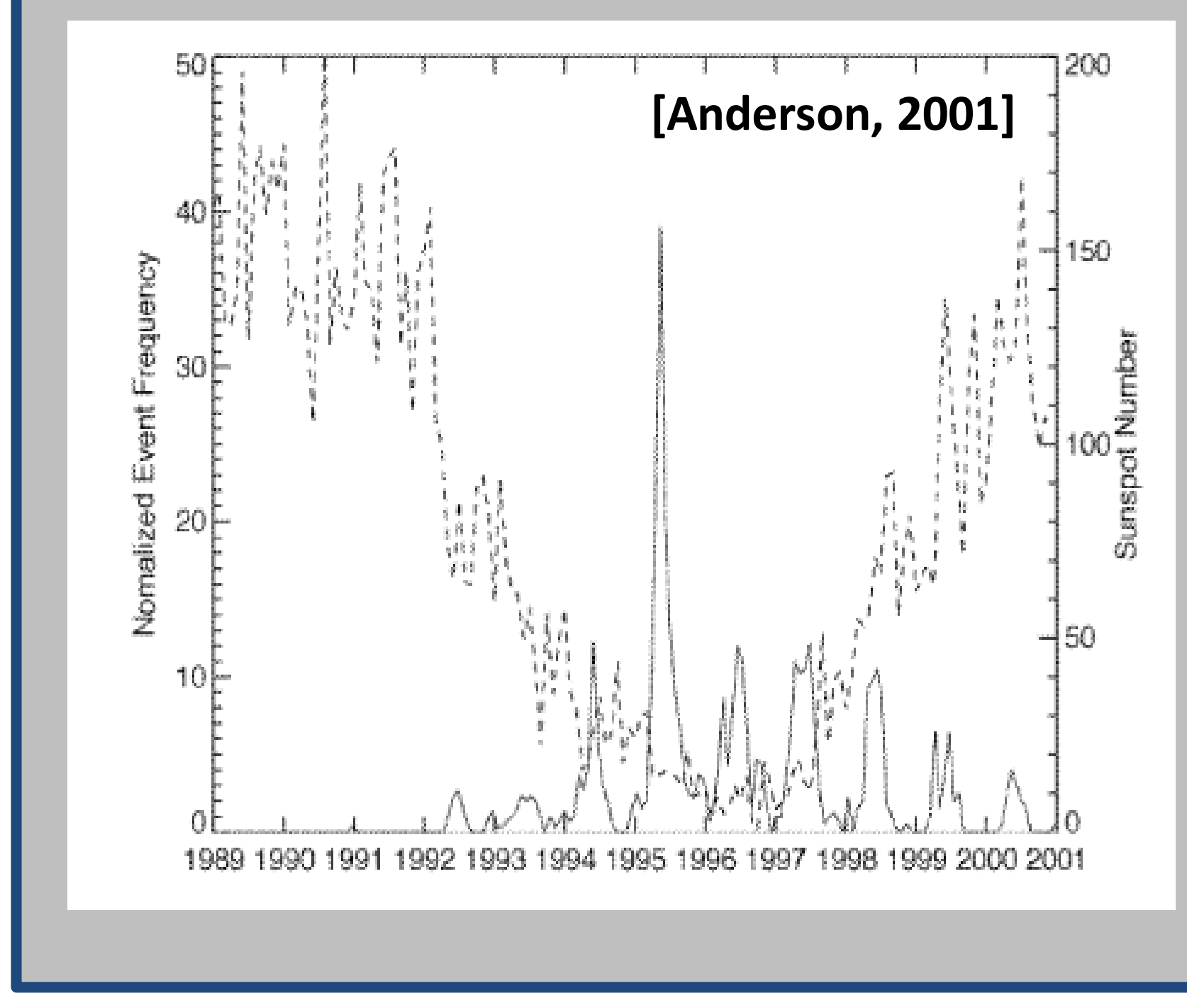


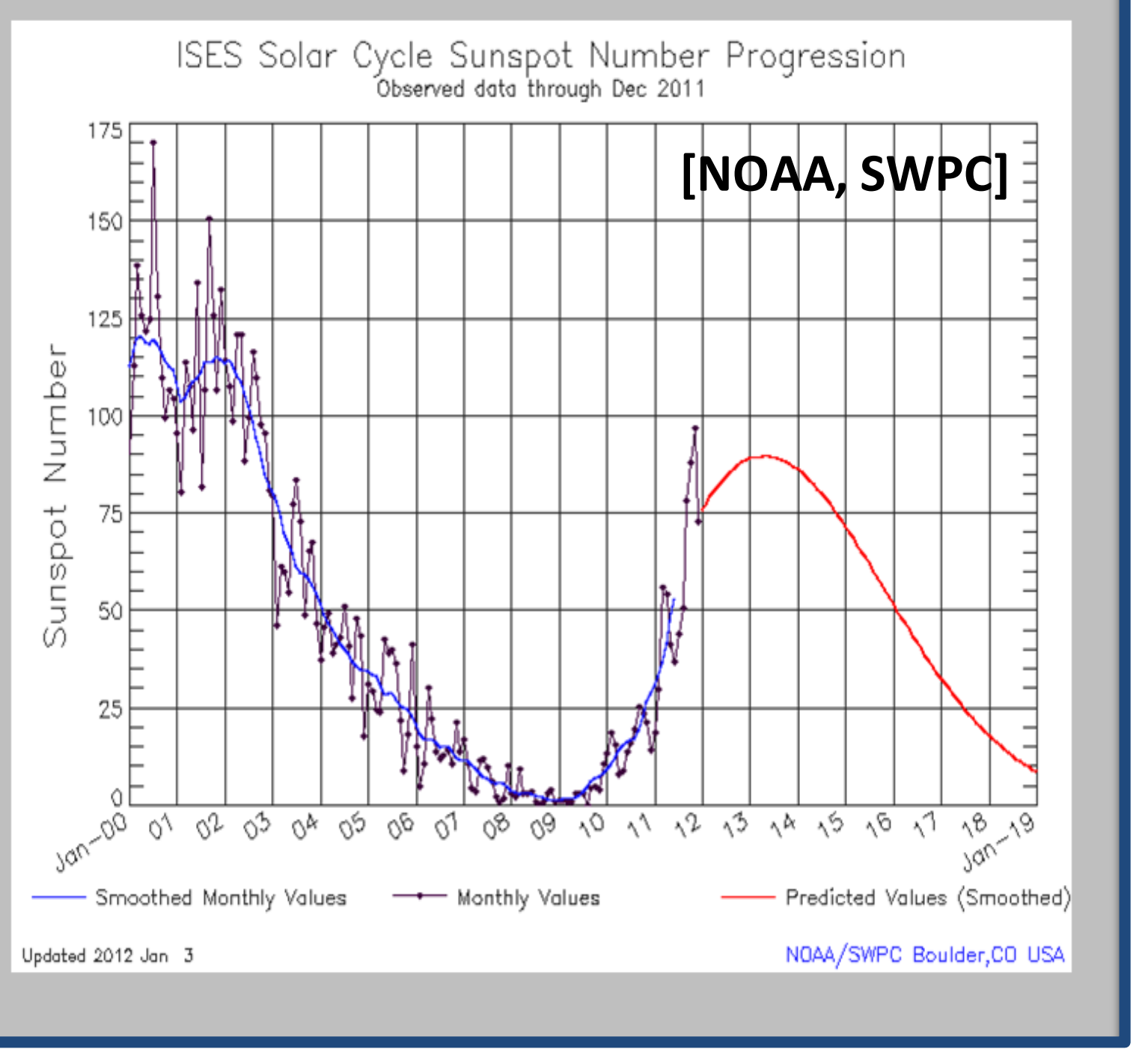
(c) Bus: 3m x 2 m x 2 m Solar array: 2m x 10 m in darkness
aluminum solar cells on Kapton

Nascap-2k surface charging simulations using a realistic harsh auroral charging environment derived from the DMSP F13 satellite for input to the charging code. The simulations show that spacecraft regardless of size are susceptible to auroral charging when their orbits encounter auroral charging environments. Frame charging develops over very short timescales on the order of a few seconds while differential charging is slower requiring minutes to develop significant differential potentials between the ground plane and insulators over the surface. The temporal history of charging will depend on the specific design details of a spacecraft and each satellite is unique.

## Discussion

Auroral charging is a potential threat to spacecraft traversing regions of auroral electron precipitation. The results presented here are derived from a review of published information on auroral charging and evaluation of additional data from the NOAA DMSP archives not included in the published studies. Additional kilovolt charging events on the same order of magnitude as the worst case events identified by *Frooninckx and Sojka*,1992 were identified from June 2011, a period characterized by an ascending (or solar medium) phase of the current solar cycle. Since extreme events are occurring as we approach the next solar maximum it is possible that charging events may be observed through the next solar maximum, an event that has not been observed previously. These results suggest that more careful examination of the full DMSP data set is warranted to determine the full range of extreme auroral charging environments possible for use in evaluating spacecraft design.





## Acknowledgements

DMSP SSJ/4 and SSJ/5 electrostatic analyzer records and Operational Limb Scan images were provided by NOAA National Geophysical Data Center. Additional SSJ/4 plots were provided by the John Hopkins University Applied Physics Laboratory.

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