ESA EUREKA satellite solar array arc damage (Image: ESA)

Surface Charging to High Voltages in the Space Environment

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Introduction

- Accumulation of excess negative charge or inductive re-distribution of charge generates potential differences between spacecraft and space (frame potential) or between two points on the spacecraft (differential potential)

- Why do we care?
  - An electrostatic discharge (ESD) results when electric fields associated with potential differences ($\mathbf{E} = -\nabla\Phi$) exceed the dielectric breakdown strength of materials allowing charge to flow in an arc
  - Damage depends on energy available to arc, $E = ½CV^2$

- Charging anomalies and failures depend on
  - Magnitudes of the induced potentials and strength of the electric fields which control how much energy is available for an arc
  - Material configuration (and capacitance)
  - Electrical properties of the materials
    - Surface and volume resistivity, dielectric constant
    - Secondary and backscattered electron yields, photoemission yields
    - Dielectric breakdown strength

Space Environment Impacts on Space Systems

Anomaly Diagnosis	Number	%
ESD-Internal, surface and uncategorized	162	54.1
SEU (GCR, SPE, SAA, etc.)	85	28.4
Radiation dose	16	5.4
Meteoroids, orbital debris	10	3.3
Atomic oxygen	1	0.3
Atmospheric drag	1	0.3
Other	24	8.0
Total	299	100.0%

[Koons et al., 2000]

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This presentation is a summary of
- Charging and electrodynamic processes leading to high voltages in space
- Examples of spacecraft potentials due to surface charging in GEO and LEO
- Lunar surface potentials
- Solar array charging

Potential Distributions on Spacecraft Surfaces

- **Electrostatic potentials**
  - Due to net charge density on spacecraft surfaces or within insulating materials due to current collection to/from the space environment
- **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

$$\frac{dQ}{dt} = C\frac{dV}{dt} = \sum_k I_k$$ **~ 0 at equilibrium**

[c.f., *Whipple*, 1981; p. 272 *Wangness*, 1986; p. 210 *Jackson*, 1975; *Maynard*, 1998]

Internal (deep dielectric) charging

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

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

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot J \quad \text{where } J = J_R + J_C$$

Electrodynamic (inductive) potentials

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

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

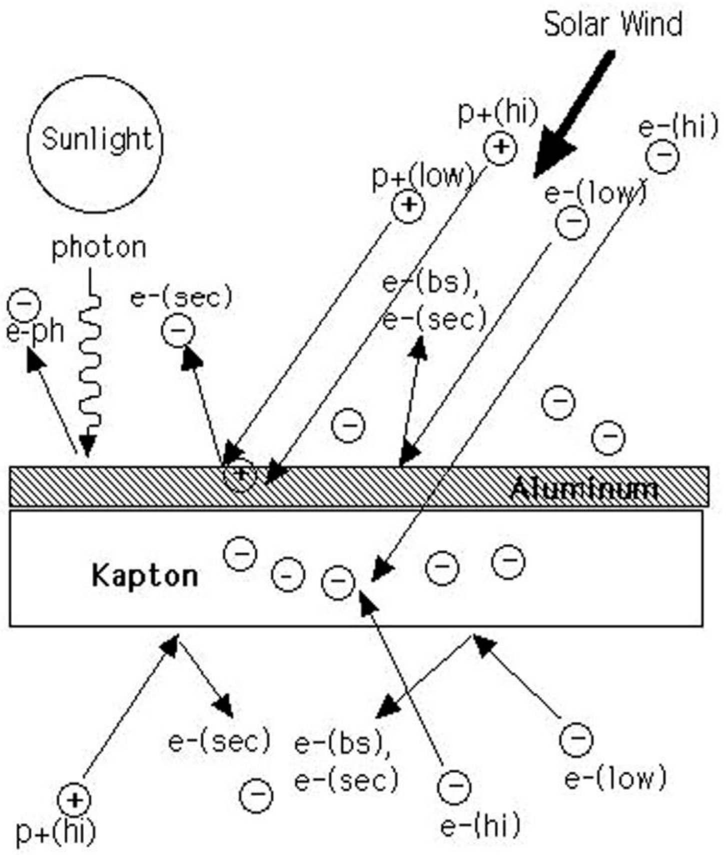
$\vec{E}' = \vec{E} + \vec{v}\times\vec{B}$ Forces equal in both frames!

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

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

Charging Physics

- Charging is the accumulation of a net charge on or within spacecraft materials. The sum of the currents = 0 at equilibrium.
  - Surface
  - Deep dielectric or internal charging



(Garrett and Minow, 2004)

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

incident ions	$+I_i(V)$
incident electrons	$-I_e(V)$
backscattered electrons	$+I_{bs,e}(V)$
conduction currents	$+I_c(V)$
secondary electrons due to I_e	$+I_{se}(V)$
secondary electrons due to I_i	$+I_{si}(V)$
photoelectrons	$+I_{ph,e}(V)$
active current sources (beams, thrusters)	$+I_b(V)$

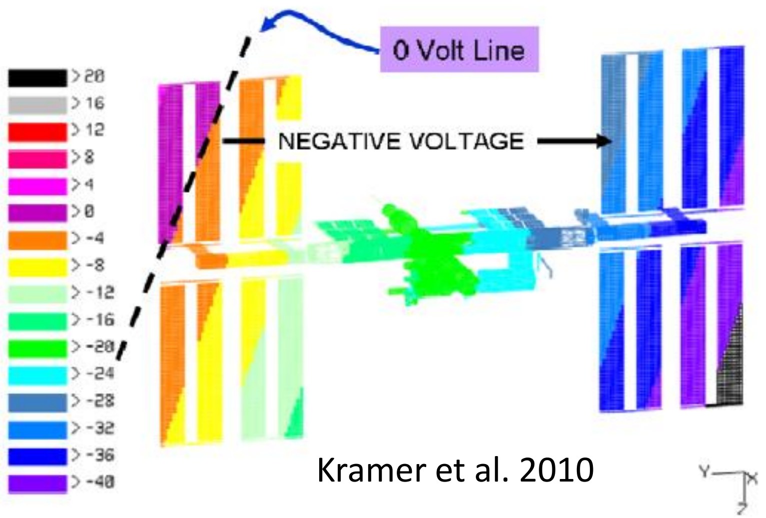
Electrodynamic Potentials

- Conductor moving across a magnetic field generates a potential difference across the conductor:

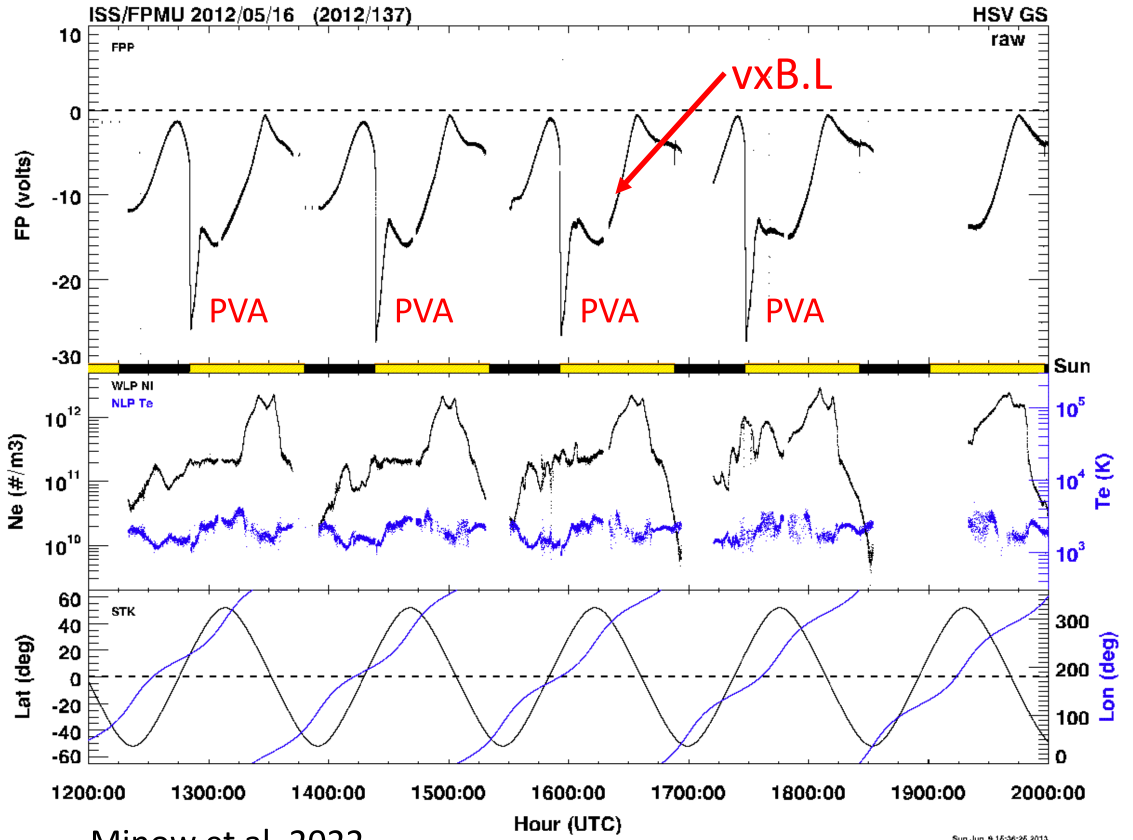
$$\Delta\varphi = v \; x \; B \; \cdot L$$

- Important primarily for spacecraft moving at high velocity in strong magnetic fields, typically low altitude spacecraft in planetary magnetospheres

- Low Earth orbit electrodynamic electric fields are ~0.4 V/m
    - v x B = (~0.5 Gauss)(~ 8 km/s) ~ 0.4 V/m
    - Typical spacecraft with L ~ 1 to 10 m results in $\Delta\varphi$ ~ 0.4 to 4 V
    - International Space Station L ~ 100 m results in $\Delta\varphi$ ~ 40 V



Kramer et al. 2010



Minow et al. 2022

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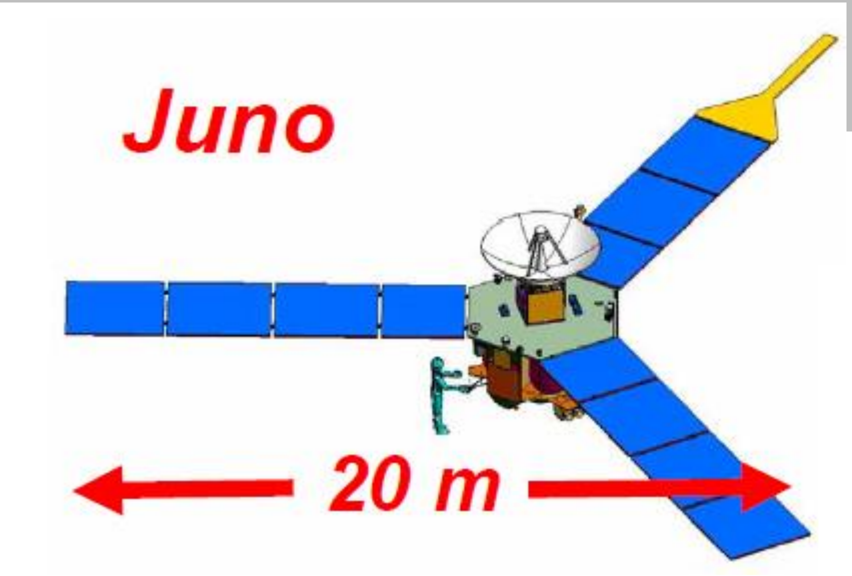
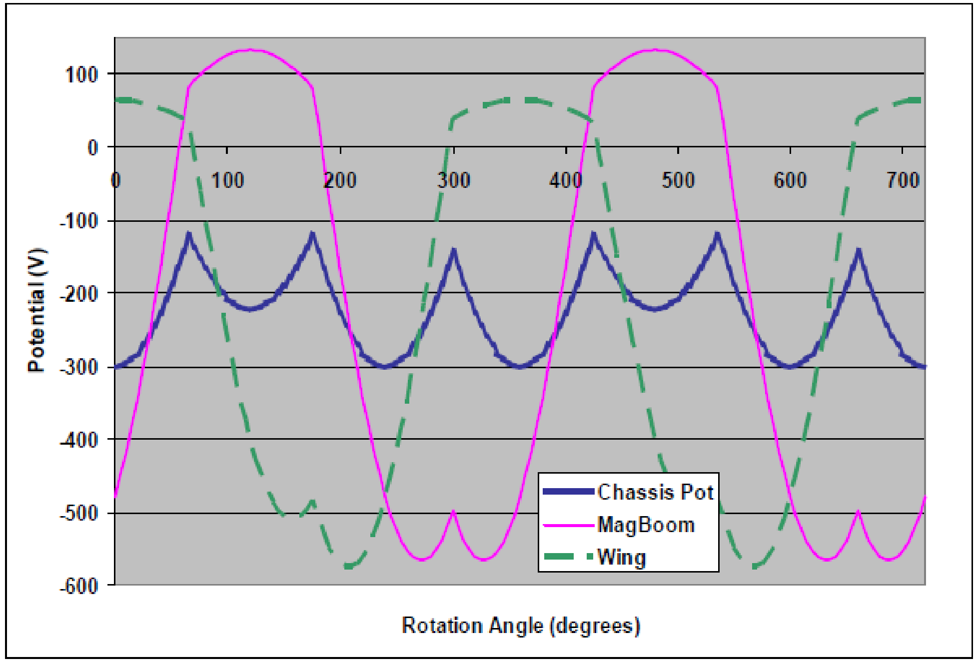
- Jupiter's magnetic field is stronger than Earth
  - ~20x magnetic field and 20,000x magnetic moment

- Juno spacecraft
  - V x B = (~10 Gauss)(~60 km/s) ~ 60 V/m
  - Juno spacecraft ~ 20 m gives $\Delta\varphi$ ~ 1200 V

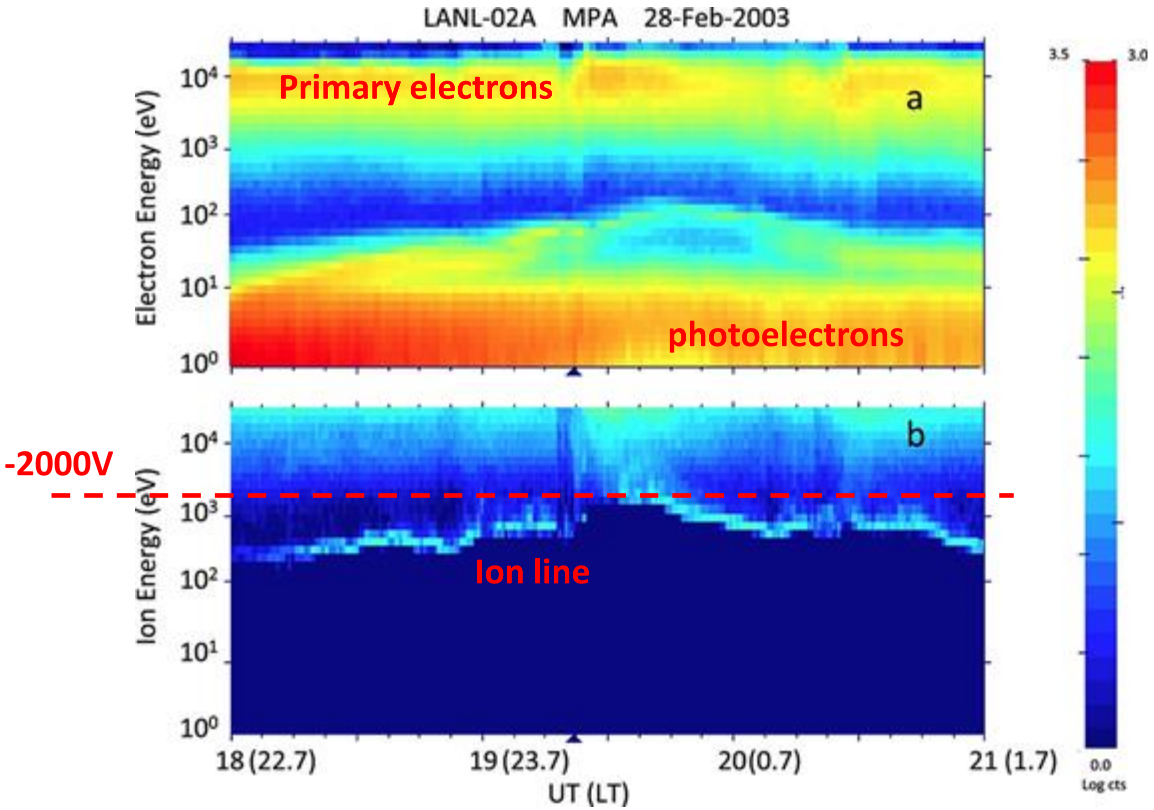




Garrett et al. 2010

Ion-Line Charging Signature

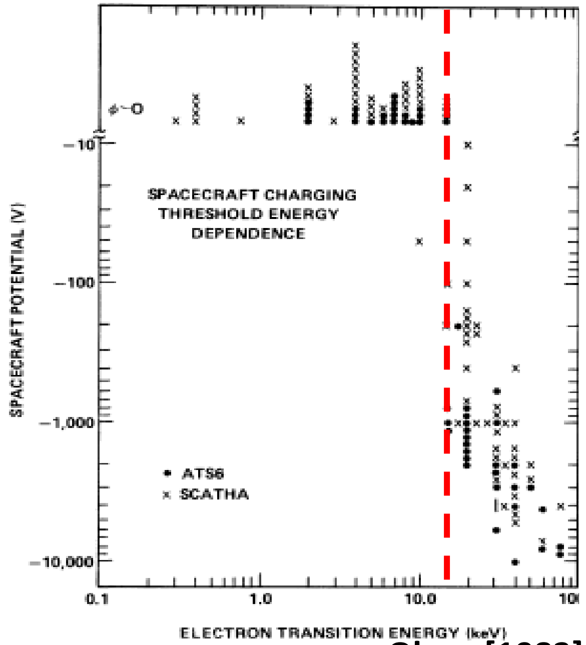
- LANL-02A in geostationary orbit
  - Spacecraft charged to potential $\Phi < 0$
- Primary electrons, $E' = E_0 - q\Phi$
  - Only electrons with energy $E_0 > |-e\Phi|$ can impact spacecraft surface
- Single charged ions attracted to $\Phi < 0$ spacecraft and impact with energy $E = E_0 + e\Phi$
  - Thermal $E_0 \sim 0$ eV ions impact with minimum energy $E = e\Phi$
  - Strong line of flux appears in the spectrogram at the spacecraft potential due to the acceleration of the thermal ions
  - Spacecraft potential estimated from the ion-line energy
- Example here shows the LANL-02A spacecraft charged more negative than -200 V for there hours and a peak charging to about -2000 V about 6 hours after local midnight
- Photoelectrons returned to spacecraft by electrostatic barrier generated by differential charging of insulators near the particle detector



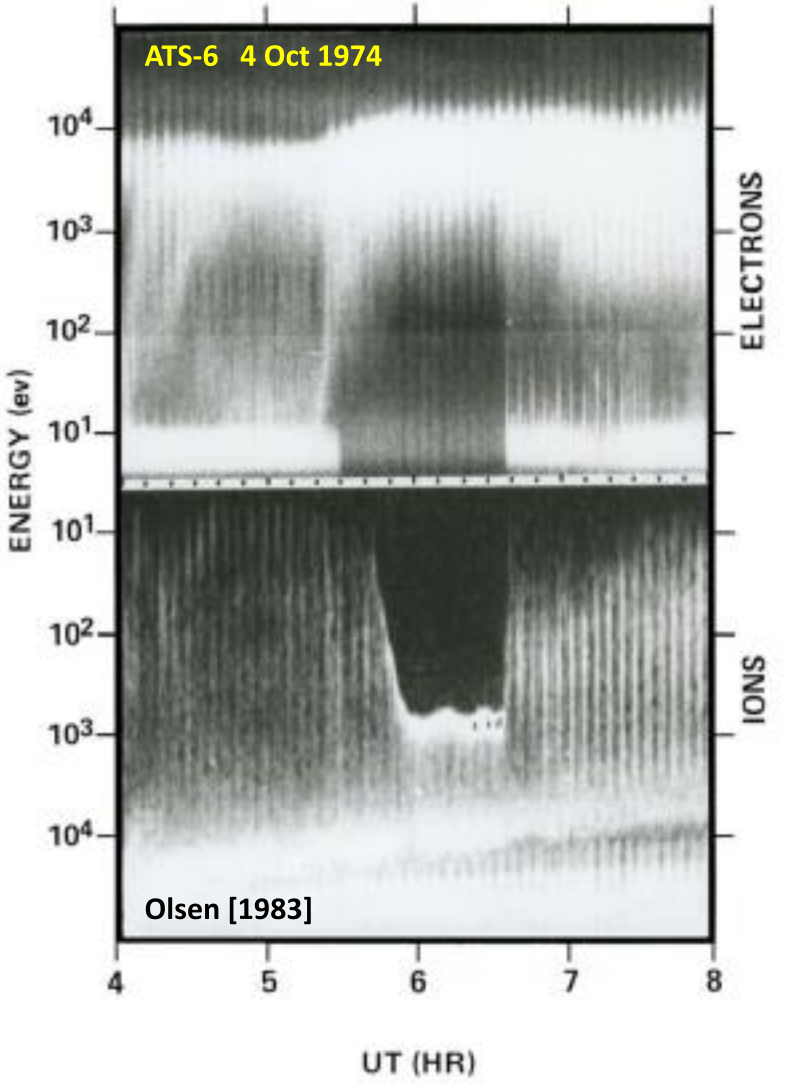
Thomsen et al., 2013

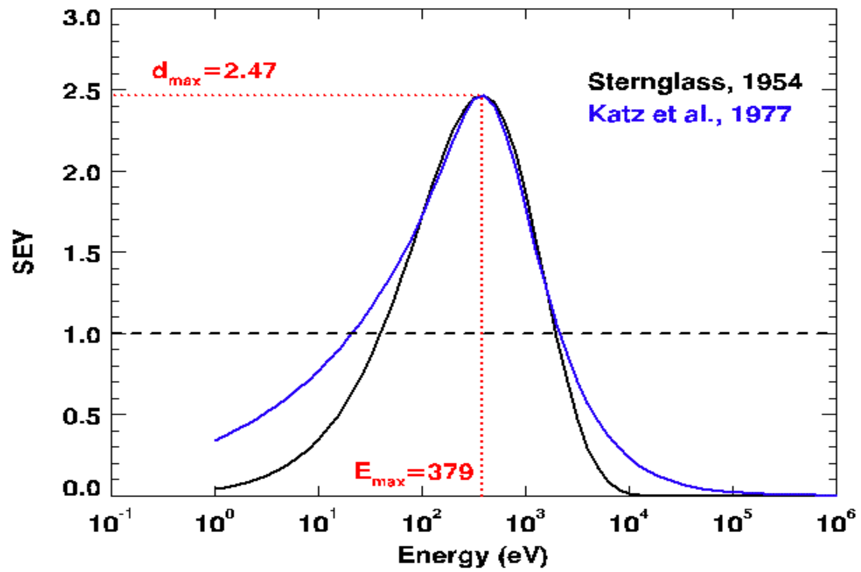
Temperature Threshold for Charging

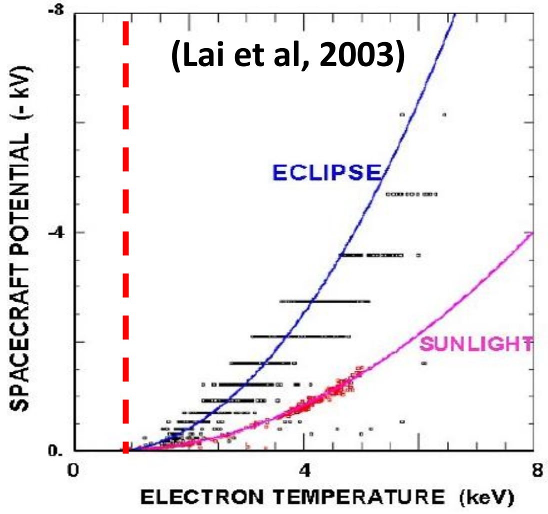
- Significant negative charging doesn't begin until enough electrons in the environment have energies greater than second cross over point of the secondary electron yield curve
- Electron energy threshold for onset of charging is due to second crossover point of secondary electron yield curves (Olsen, 1983)
- Charging above threshold can reach negative potentials of -100's V to -1000's V and extremes to -10,000's V



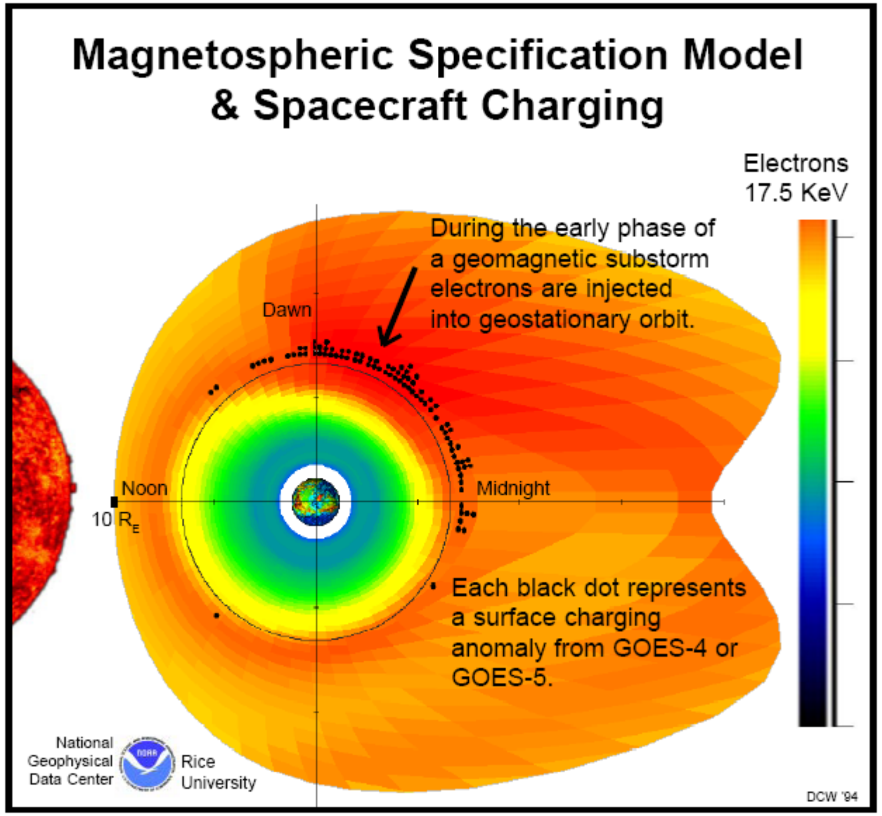
Olsen [1983]



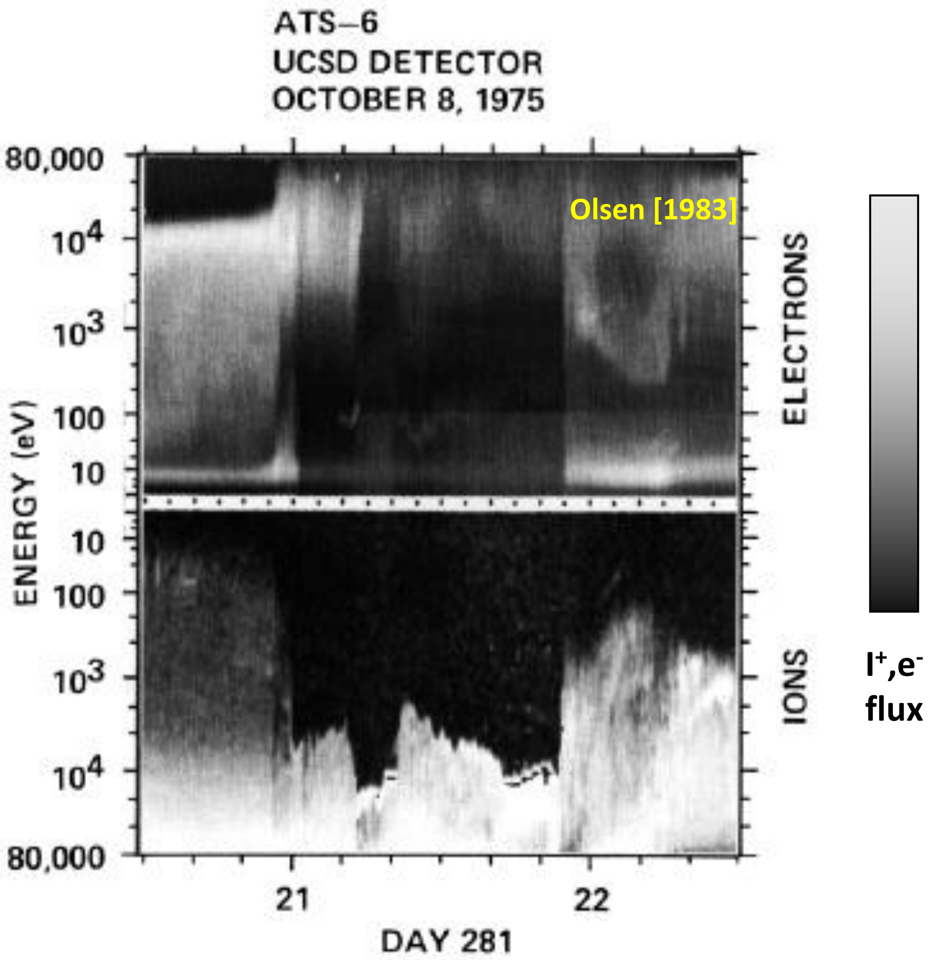




GEO Surface Charging



Surface charging anomalies typically occur in midnight to dawn local time sector where hot electrons are injected during geomagnetic substorms



Record ATS-6 charging event
$\Phi \sim -19$ kV

LEO Auroral Charging

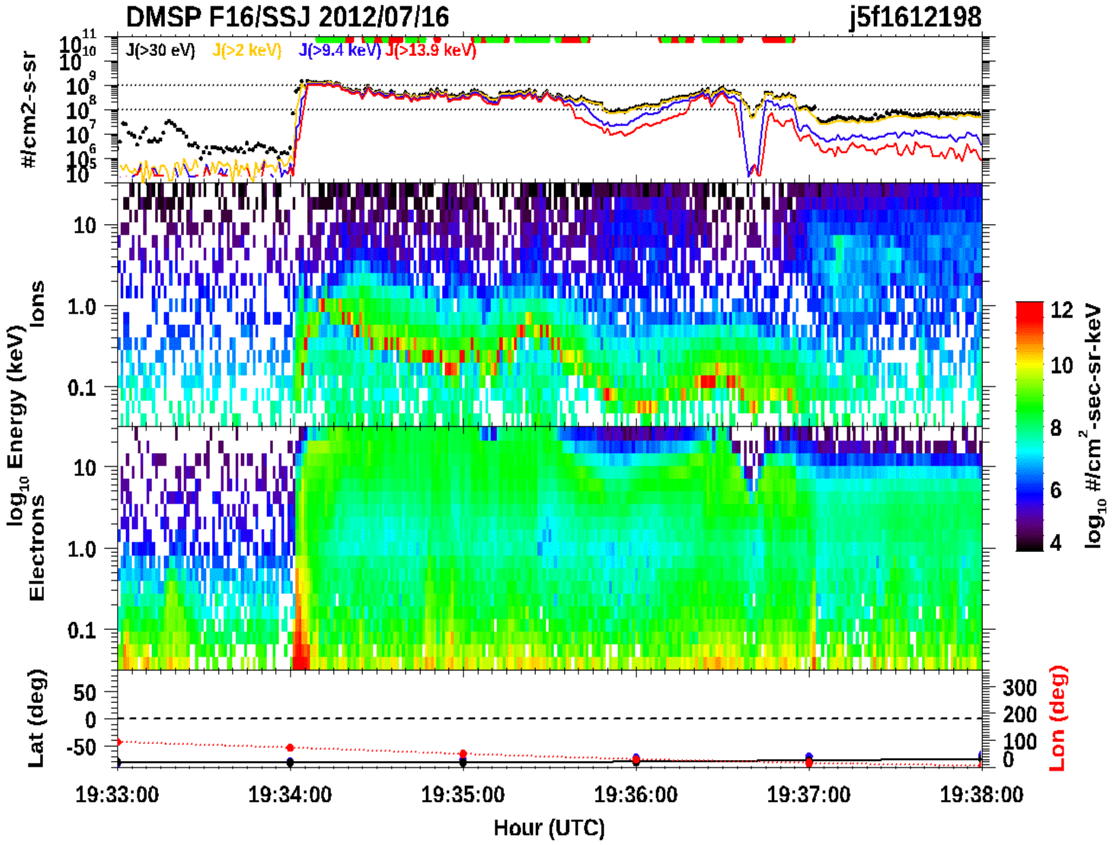
- Spacecraft in LEO polar orbits passing through energetic auroral electrons will charge to potentials of -100's V to -1000's V (Gussenhoven et al. 1985; Yeh and Gussenhoven, 1987, Frooninckx and Sojka, 1992)

- **DMSP (835 km, circular, 98° inc)**
  - Solar Cycle 22-23, 12 years (Anderson 2012):
    1600 events with ϕ ≤ -100 V
  - Solar Cycle 23-24, 11 yeaers (Meng et al. 2019):
    2493 events with ϕ ≤ -100 V
  - Extremes of -1400 V to -2000 V

- **Freja (601 km x 1756 km x 63° inc)**
  - 1.5 year period, altitudes between 1500 km – 1700 km
    39 events with ϕ ≤ -100 V
  - Extreme of -3000 V

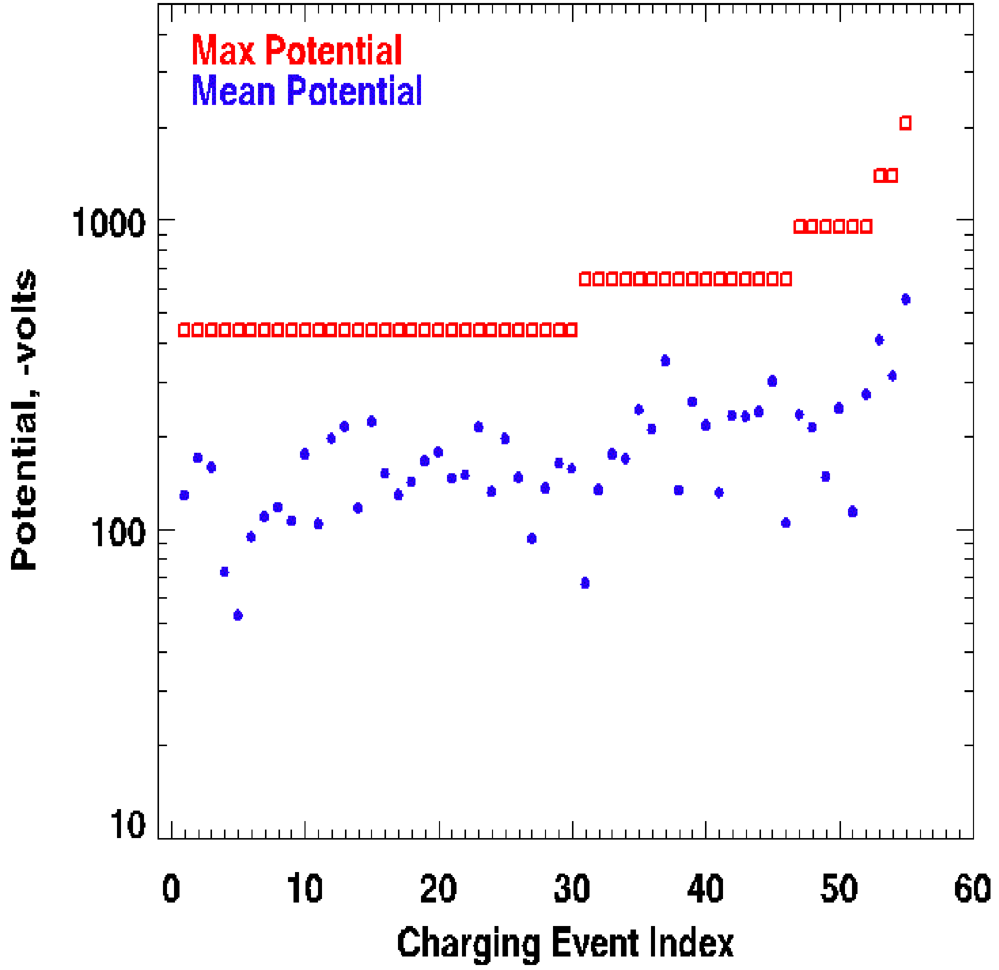
- **Jason-3 (1,336 km, circular, 66° inc)**
  - 2+ year period at solar minimum
    81 events with ϕ ≤ -100 V
    4 events with ϕ ≤ -1000 V
  - Extreme of -2440 V

DMSP F16 Charging to -1000 V



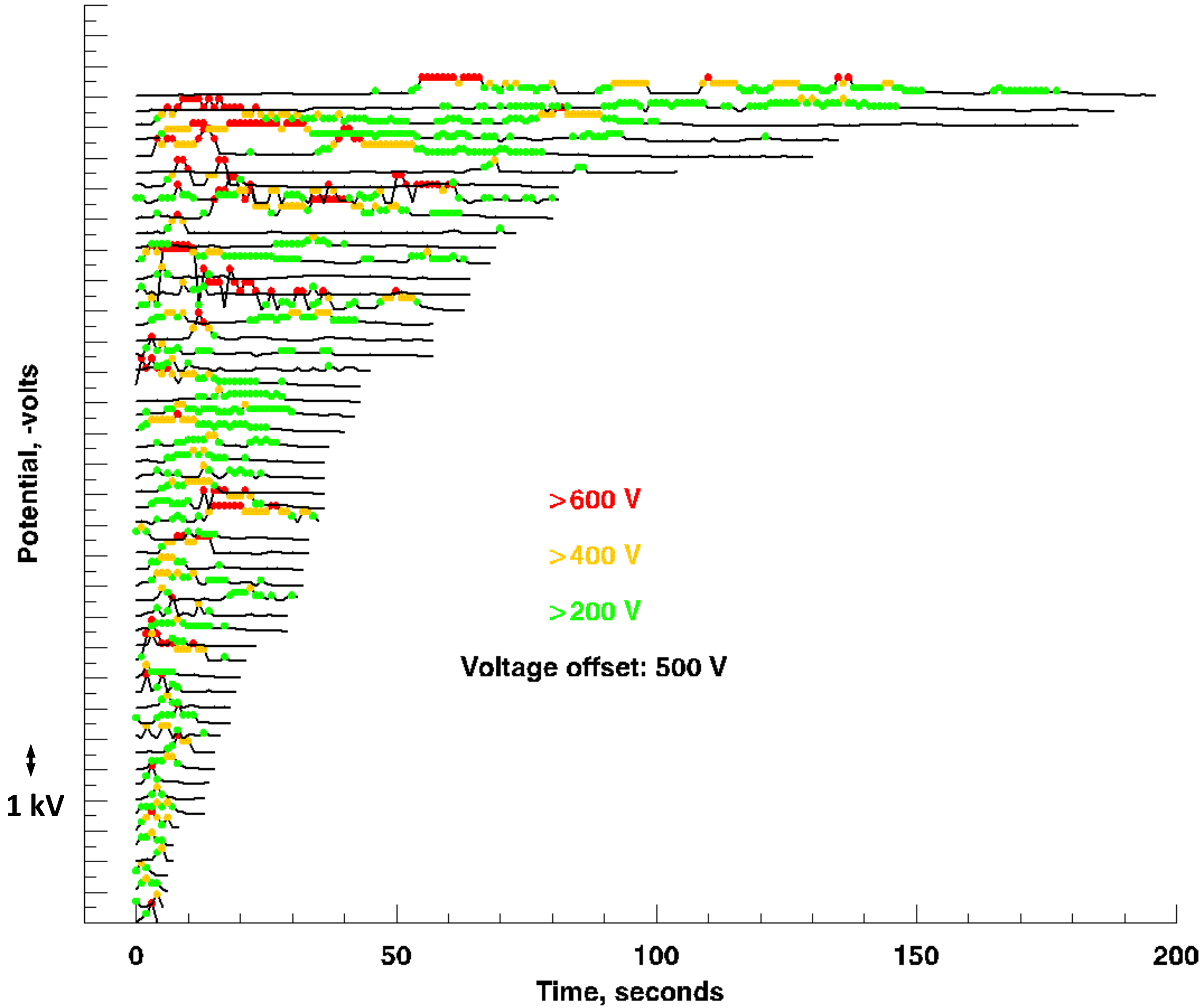
Maximum and Mean Potentials (

- Minow et al. 2014 study of 54 DMSP charging events with maximum negative potentials Φ ≤ -400 V



Potential (volts)	# seconds ≥potential	% records ≥ potential
6460	0	0.00
4400	0	0.00
3000	0	0.00
2040	7	0.26
1392	12	0.44
949	43	1.59
646	166	6.15
440	386	14.30
300	680	25.19
204	1005	37.24
139	1360	50.39
95	1685	62.43
65	2046	75.81
44	2349	87.03
30	2699	100.00

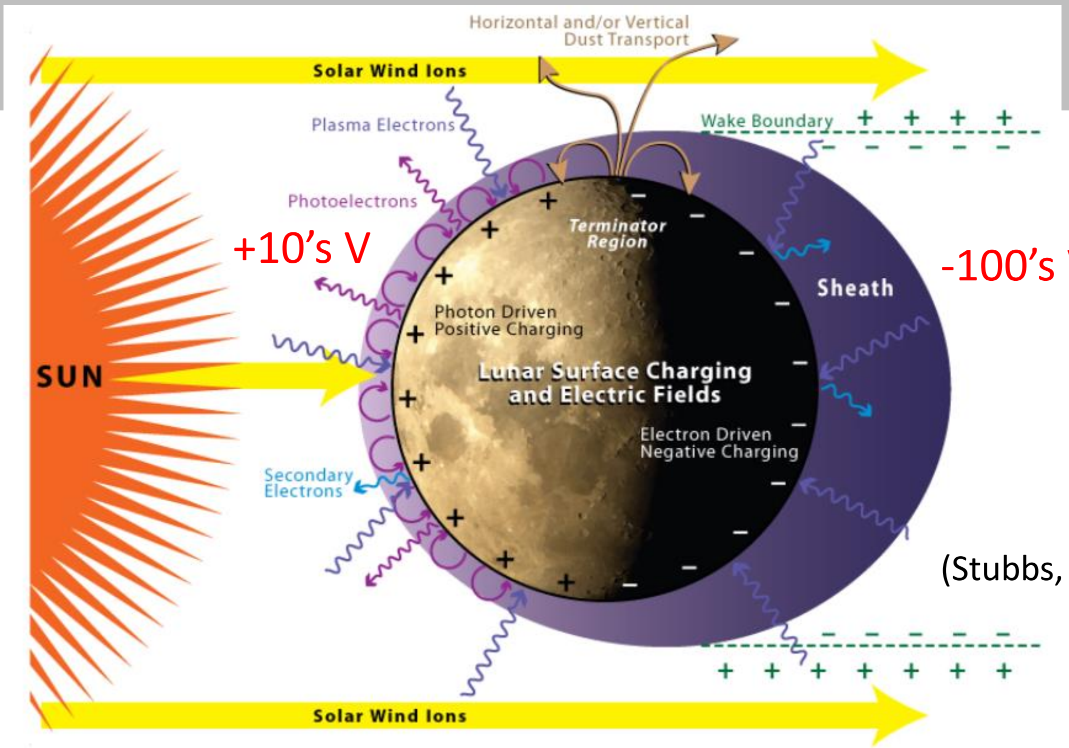
Potential Time Histories



(Minow et al. 2014)

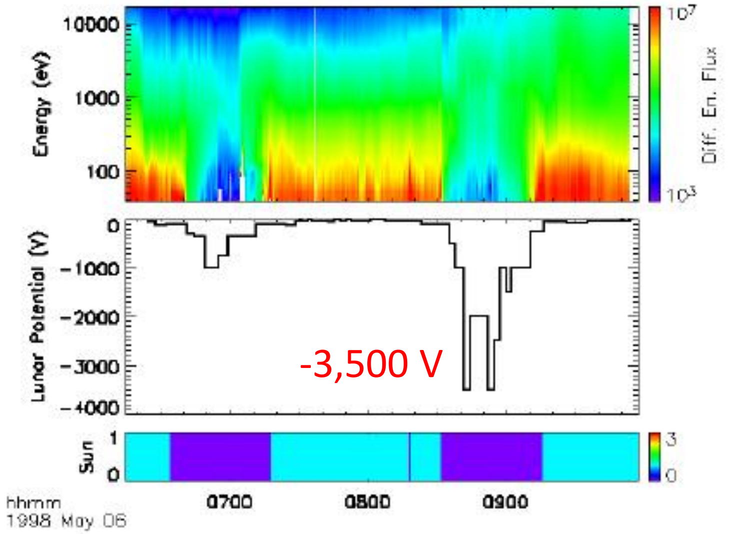
Lunar Surface Charging

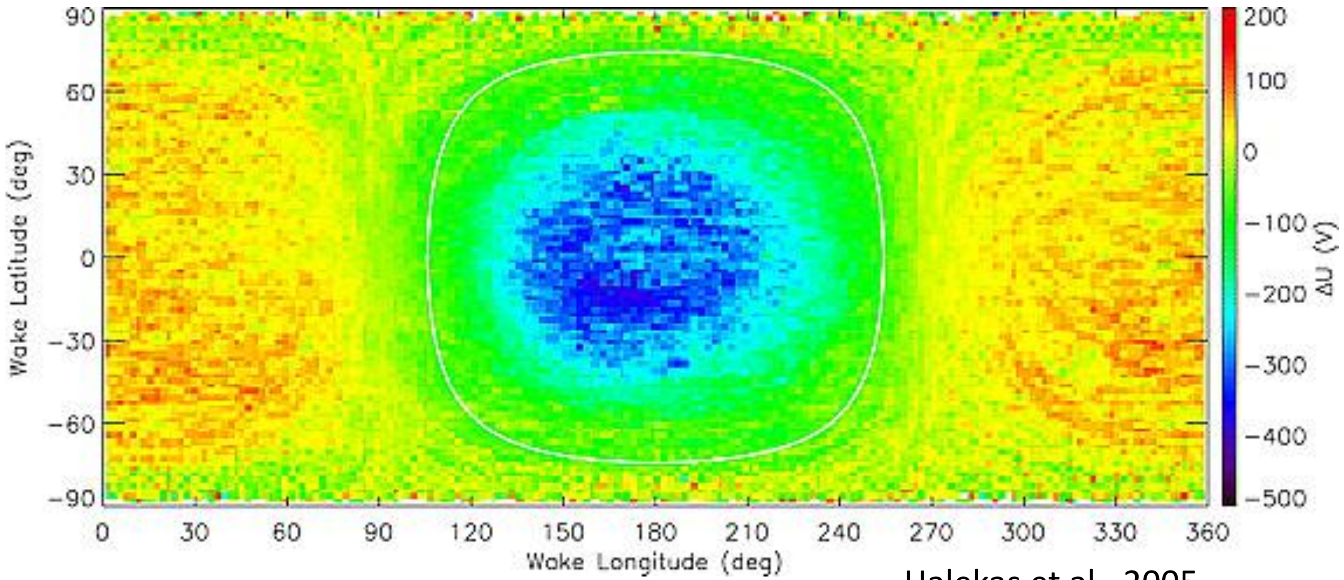
- The surface of the Moon is exposed to the charged particle environment in space without protection of an intrinsic magnetic field or an atmosphere
- Daytime charging is dominated by photoemission resulting in surface potentials to +10’s V
- Night charging is dominated by plasma charging in the lunar wake with typical surface potentials of -200 V to -300 V
- Extremes at night to -1,000’s V during solar particle events



(Stubbs, 2007)

Halekas et al., 2008





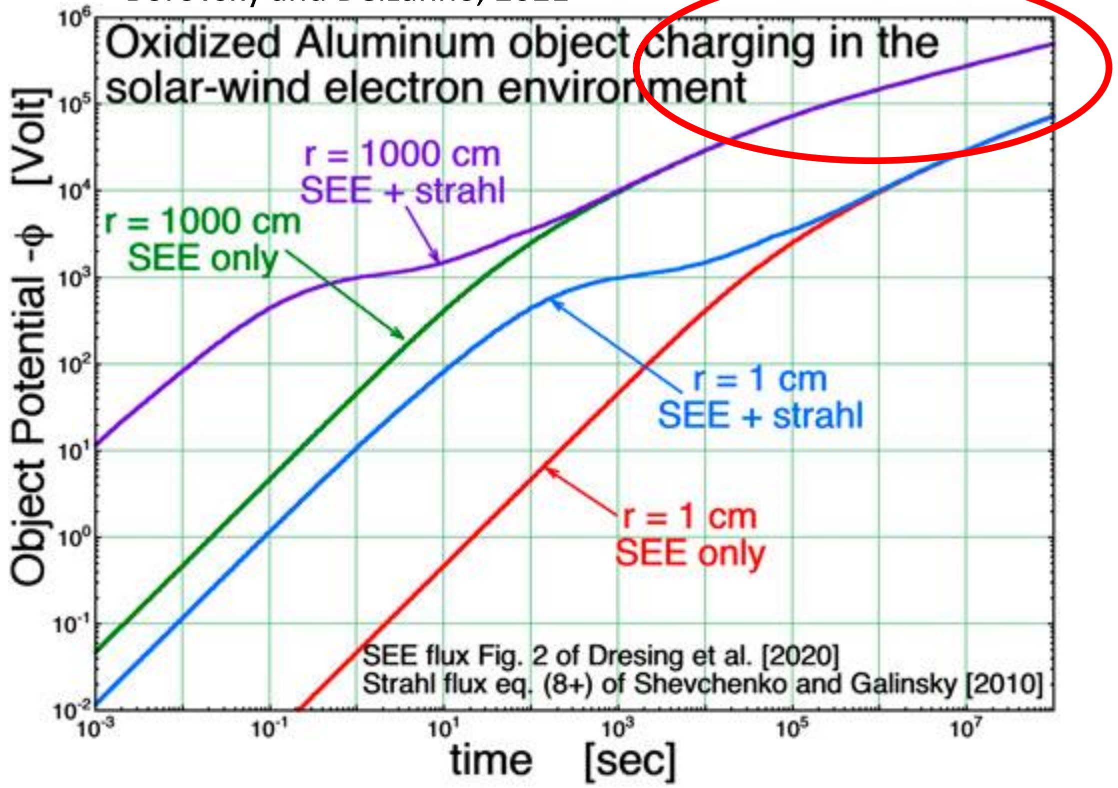
Halekas et al., 2005

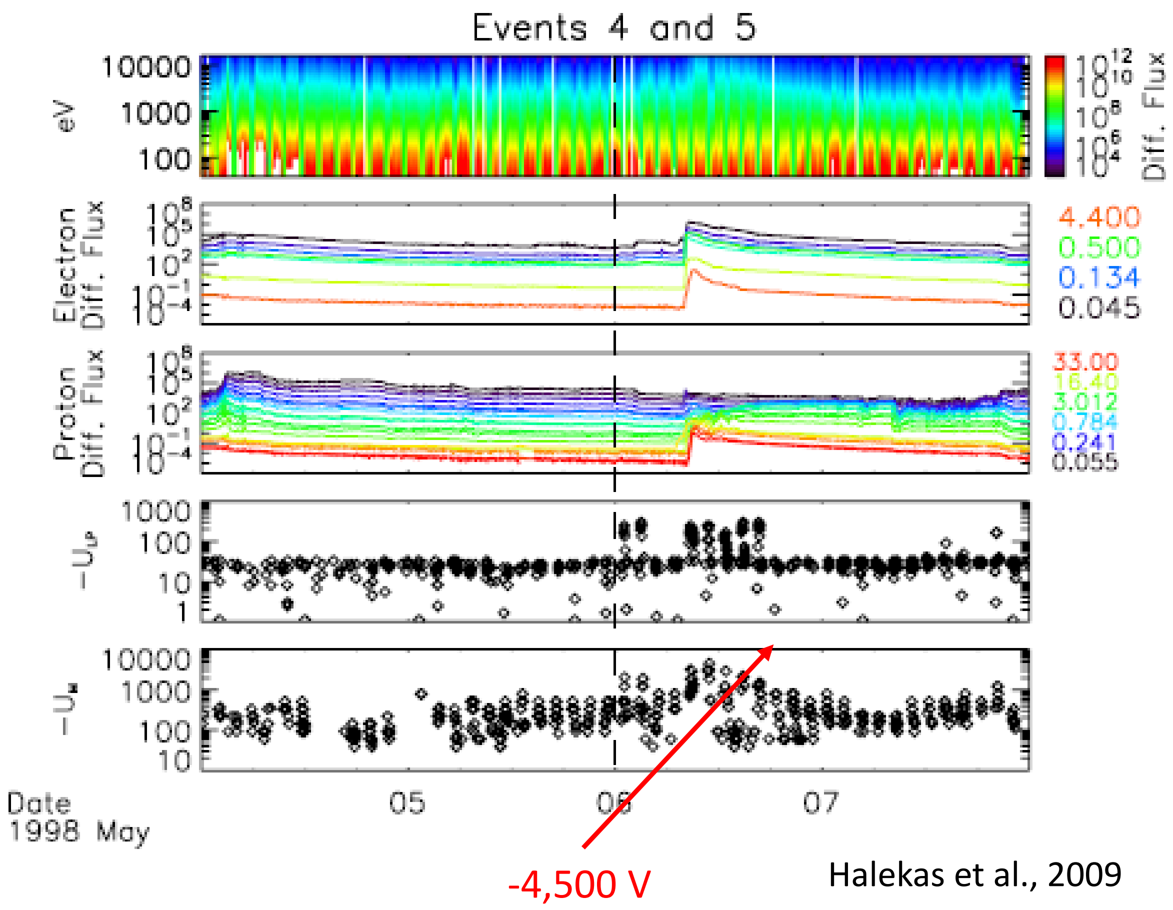
Extreme Lunar Surface Charging

- Lunar surface potentials of -1000’s V have been observed during solar particle events rich in energetic electrons

- Recent analytical models predict lunar surface potentials in the range of 10’s kV to 100’s kV during long duration solar energetic electron events! These have not been observed to date.

Borovsky and Delzanno, 2021



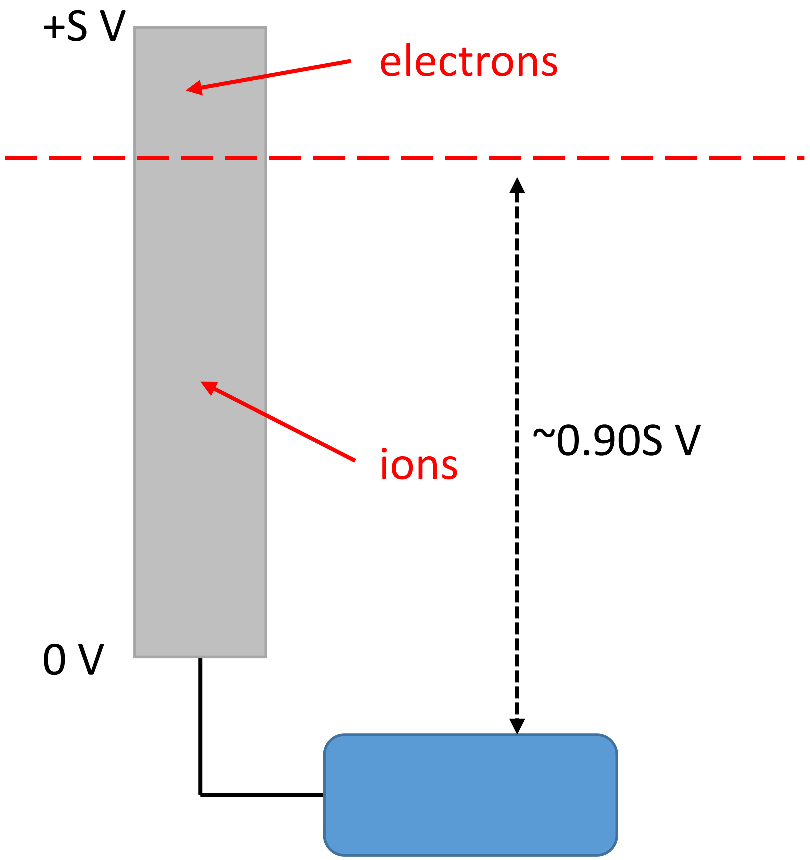


Halekas et al., 2009

4.5 kV is the most extreme lunar surface potential observed to date

Photovoltaic Array Interaction with Plasma Environment

- **Spacecraft with PVA grounded on negative end to vehicle can exhibit negative charging to ~90% of the array string voltage**
  - Minor issue for low ~30 V string voltages that have widely been used on US spacecraft
  - Can be an issue for high voltage systems with string voltages of 100’s V
  - Probability for arcing increases dramatically in LEO when the string voltage exceeds ~200 V



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- **Upper Atmospheric Research Satellite (UARS)**
  - NASA, SWRI
  - 09/1991 – 09/2005 (decommissioned)
  - Orbit: 574 km x 575 km x 57° inc
  - PVA voltage varies from 100 V (cold) to 75 V (warm)
  - Charging at eclipse exit to ~ -90 V

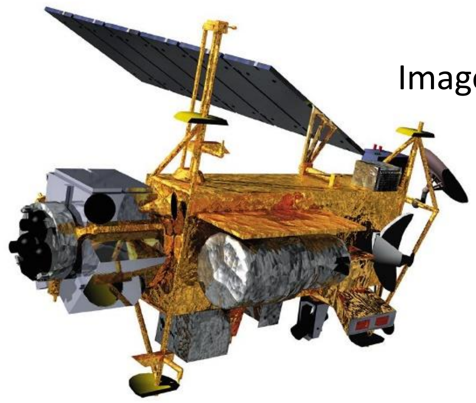
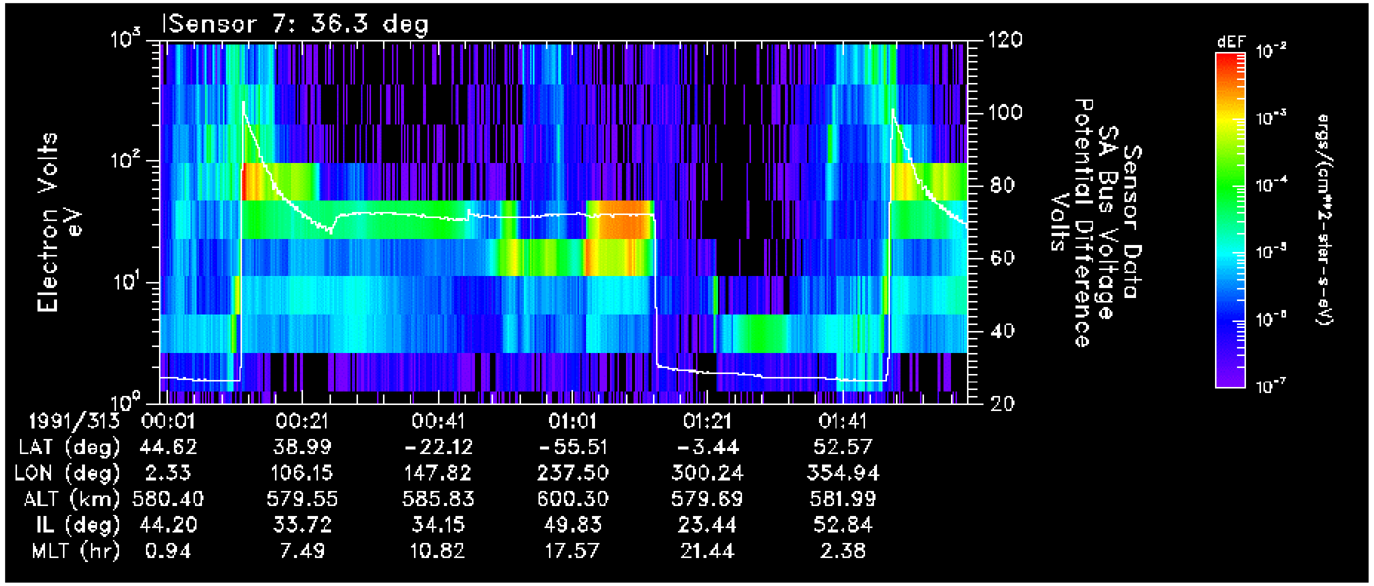


Image: NASA



UARS solar array voltage and satellite frame potential (Frahm, 2000; Carruth and Vaughn, 2000)

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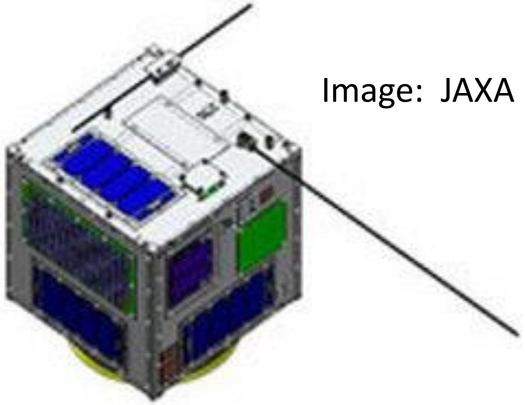


Image: JAXA

- **HORYU-II**
    - JAXA, Kyushu Institute of Technology
    - 05/2012 – operational?
    - Orbit: 651 km x 671 km x 98.2° inc
    - High voltage test PVA to 350 V
    - Charging at eclipse exit observed to over -300 V

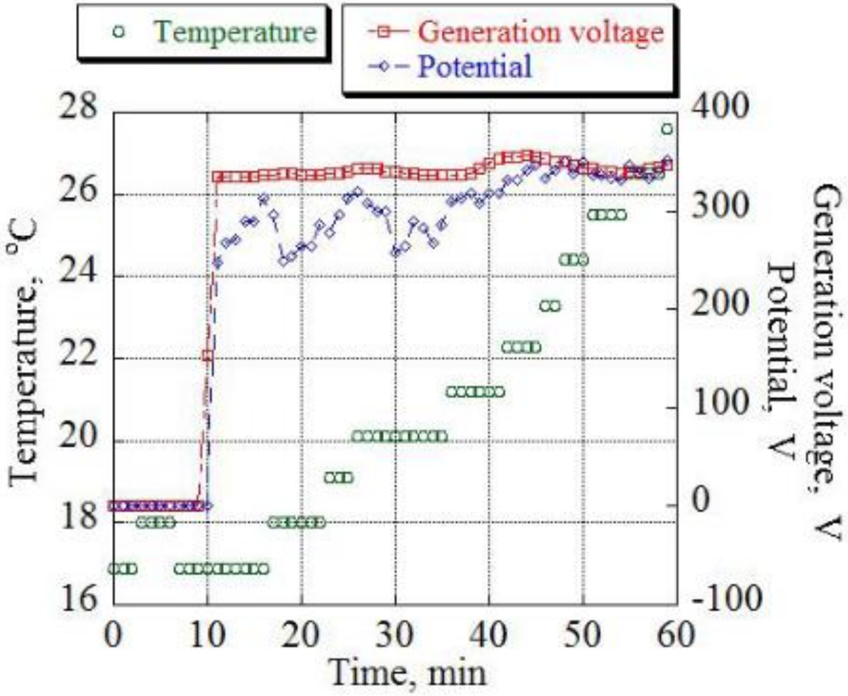


Figure 5: Result of 300V generation

(Seri et al., 2013; Cho et al., 2014)

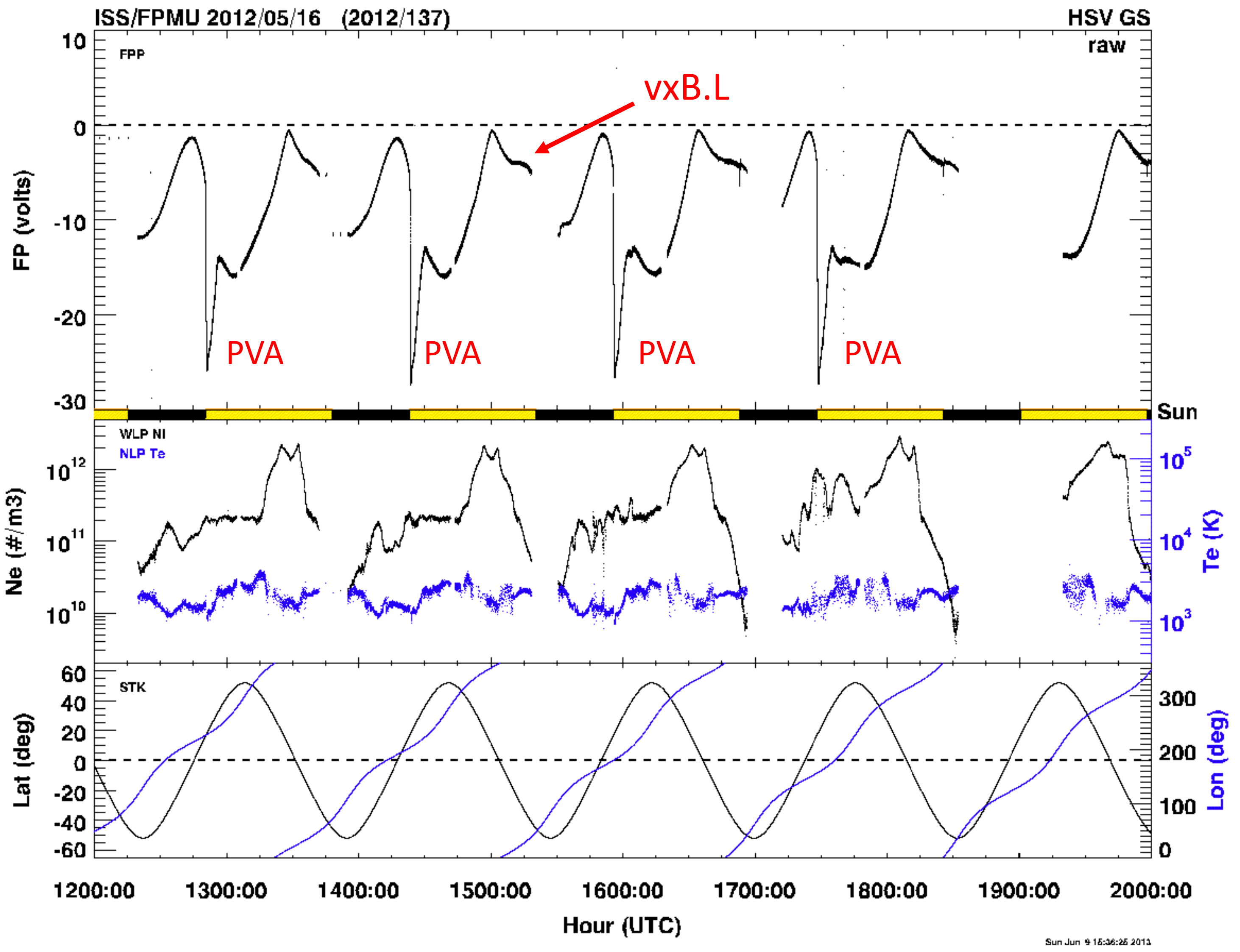
ISS Potential Variations

- ISS potential variations are due to
  - Current collection by US 160 V photovoltaic arrays (PVA)
  - Inductive (vxB).L across structure
  - Auroral charging
  - Visiting vehicles with high voltage PVAs
  - Payloads with current sources

- ISS structure is generally negative with respect to plasma since PVAs are grounded to structure on the negative end of the arrays

- Charging peaks following eclipse exit when arrays are biased, current collecting surfaces are in ram, and batteries are charging

- Charging decreases over daylight segment of orbit as strings are shunted when power needs decrease and arrays tracking the Sun rotate into wake



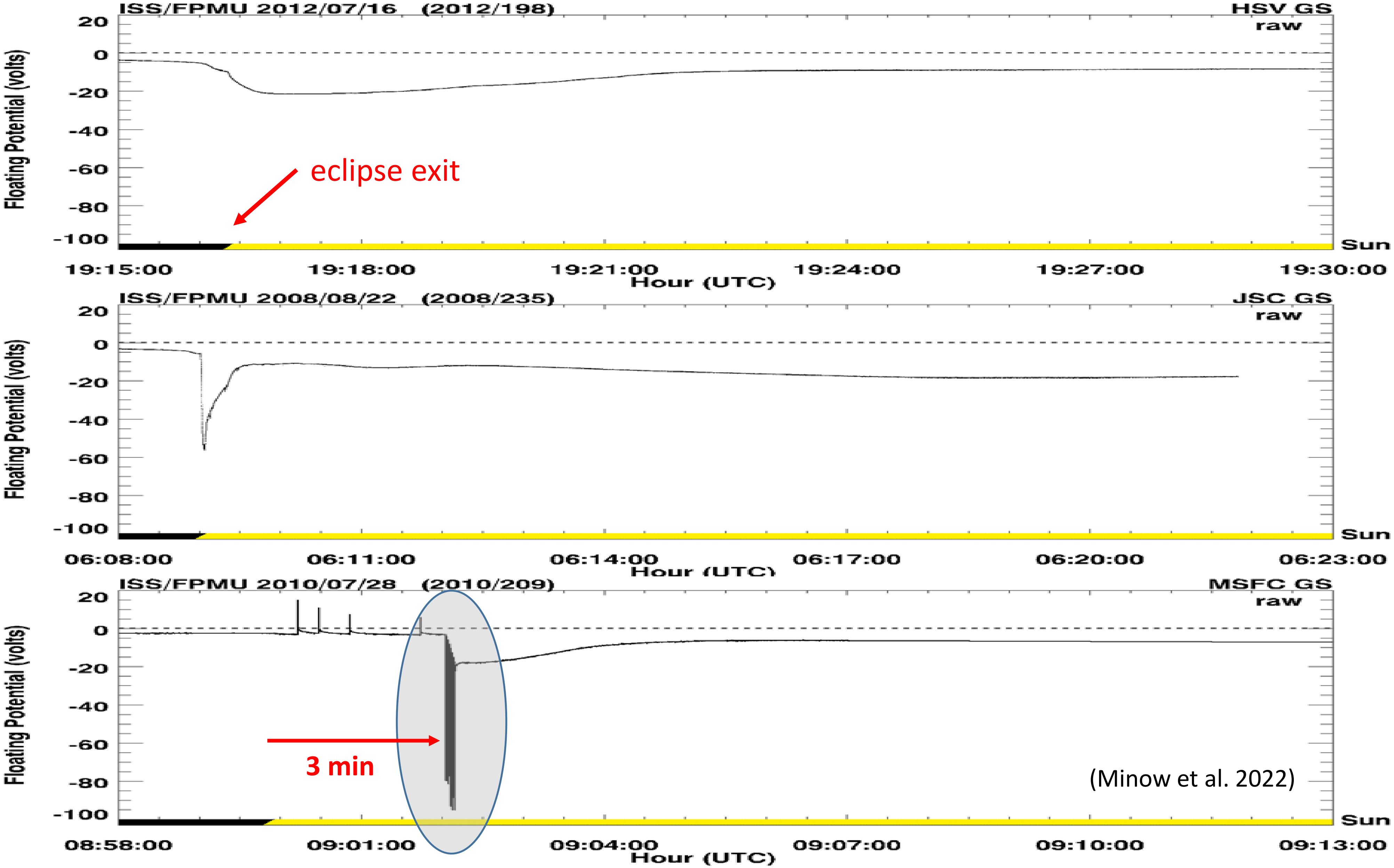
(Minow et al. 2022)

PVA Negative Charging

Normal

Rapid Charging Event (RCE)

Sunlight Unshunt

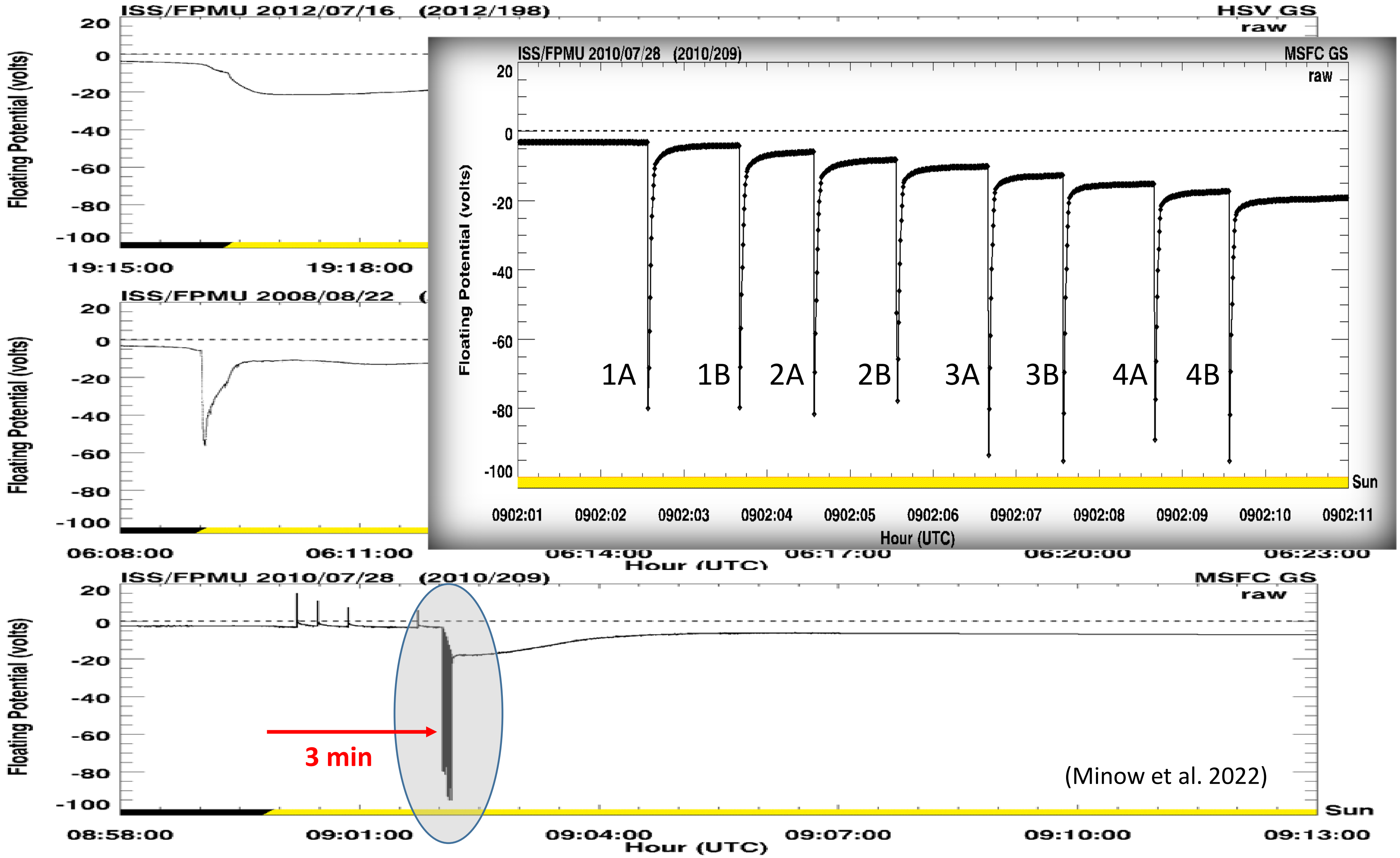


PVA Negative Charging – Sunlight Unshunt Experiment 2010

Normal

Rapid Charging Event (RCE)

Sunlight Unshunt



ISS PVA Charging Statistics and Solar Cycle

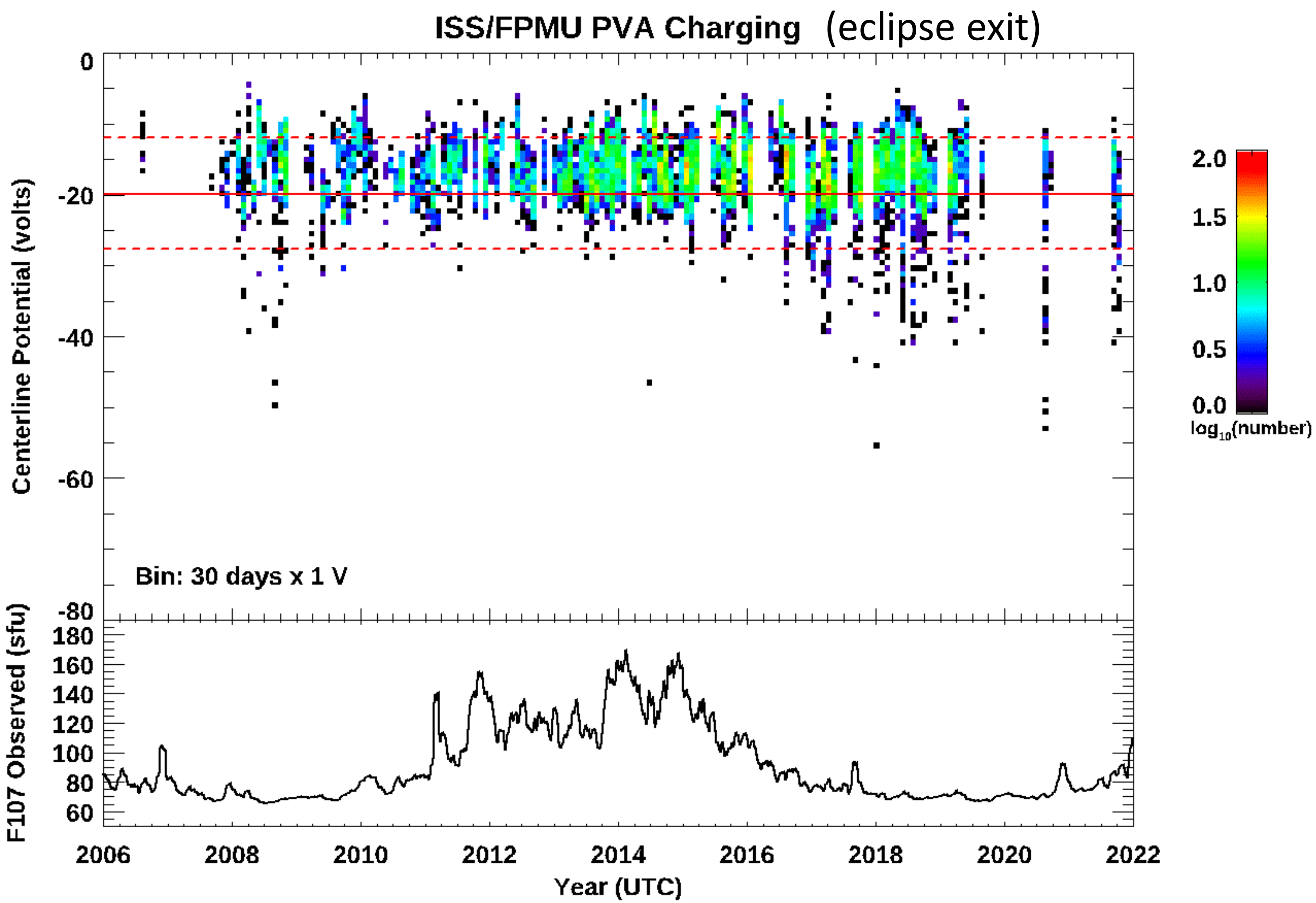
- PVA normal negative charging typically peaks in the range of -10 V to -30 V:

5%	-12.0 V
50%	-19.9 V
95%	-27.6 V

- Largest PVA RCE negative charging in the -35 V to -70 V range occurs at eclipse exits with low plasma densities

- RCEs correlate with solar cycle (because the low plasma density events are a function of solar activity)

- Largest ISS charging events observed to date are in the range of -90 V to -100 V and occur during PVA unshunt operations in full sunlight




ESA EUREKA satellite solar array arc damage (Image: ESA)

Questions?