SPACECRAFT CHARGING:

INCOMING AND OUTGOUNG ELECTRONS

Shu T. Lai

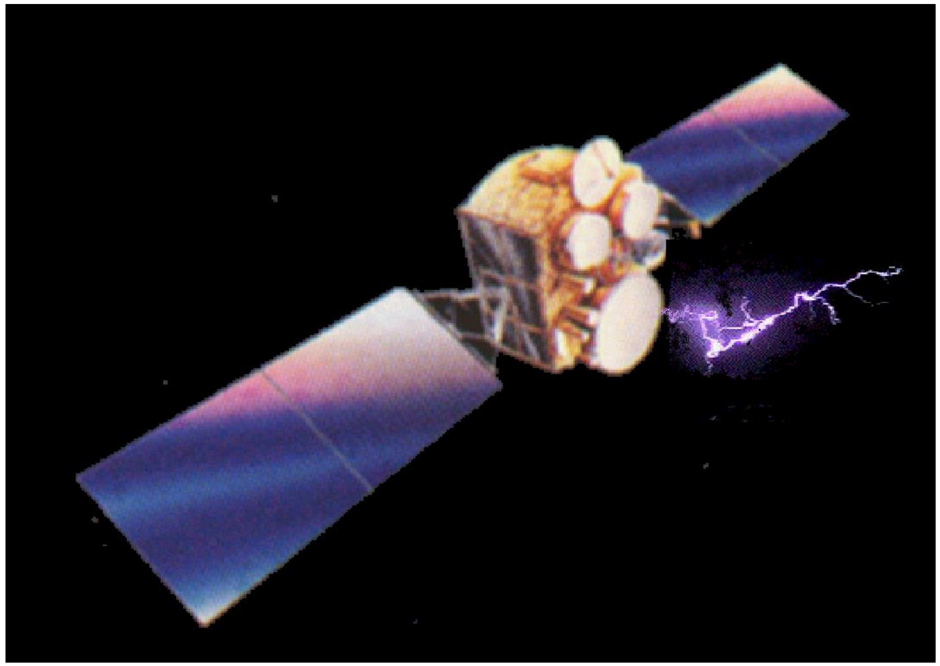
Jun, 2012

OUTLINE

- Introduction to Spacecraft Charging
- Incoming currents
- Outgoing currents
- Critical temperature: Theory and observations
- Outgoing electron yields depend on surface conditions
- Conclusions

Spacecraft Charging
Adverse Effects

Spacecraft Charging is Harmful to the Health of Onboard Electronics

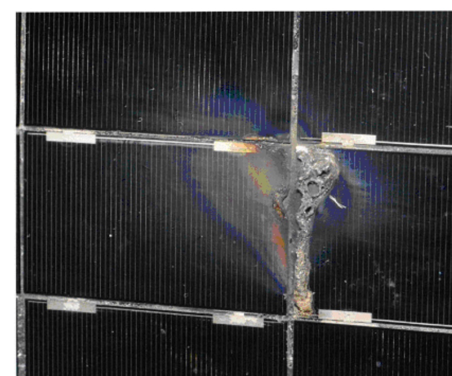


Charging affects

- Scientific measurements
- Telemetry signals
- Electronic communications

Discharges degrade

- Solar cells
- Controls
- Navigation



Spacecraft Charging

Leading Cause of Spacecraft Failures

Missions Terminated

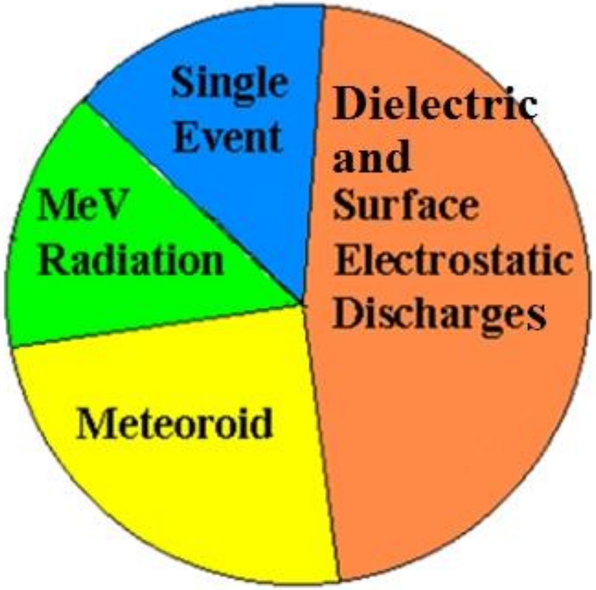
Due to the Space Environment

Geosynchrnous Satellite

VEHICLE	DATE	CAUSE (*)
DSCS II	1973	ESD
GOES 4	1982	ESD
DSP Flight 7	1985	ESD
Feng Yun 1	1988	ESD
MARECS A	1991	ESD
MSTI	1993	SEU
Hipparcos	1993	MRD
Olympus	1993	Meteoroid
SEDS 2	1994	Meteoroid
MSTI 2	1994	Meteoroid
IRON 9906	1997	SEU
INSAT 2D	1997	ESD
TELSTAR401_	1998	MRD

(*) *ESD = Electrostatic discharge*
SEU = Single event upset
MRD = MeV radiation dosage

Cause of Failure

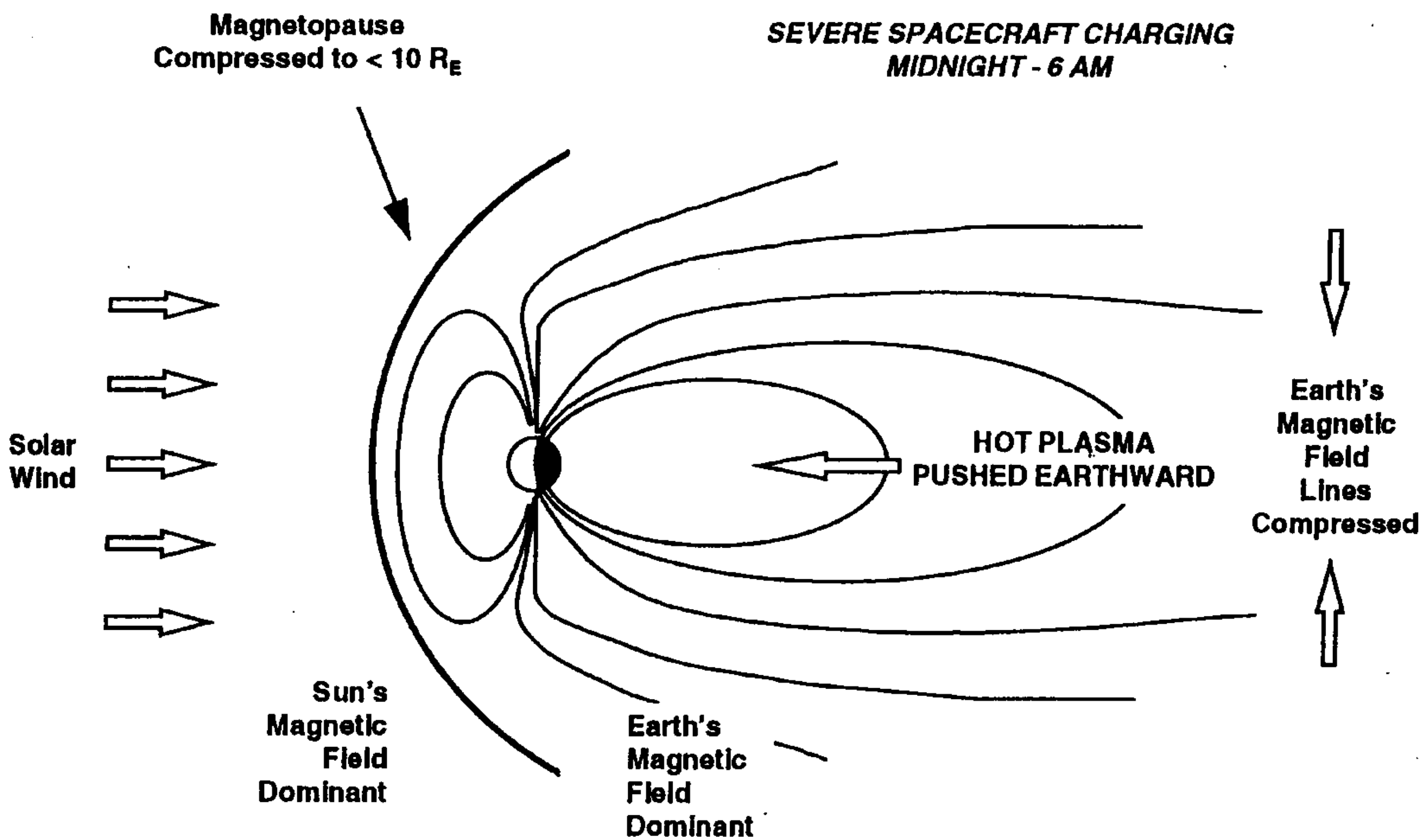


Ref: Koons, et al., SMC-TR-00-10 (2000)

Most Mission Terminated were due to Dielectric and Surface Electrostatic Discharges

Push and Pull of the Magnetosphere

Local Time Dependence of Spacecraft Charging

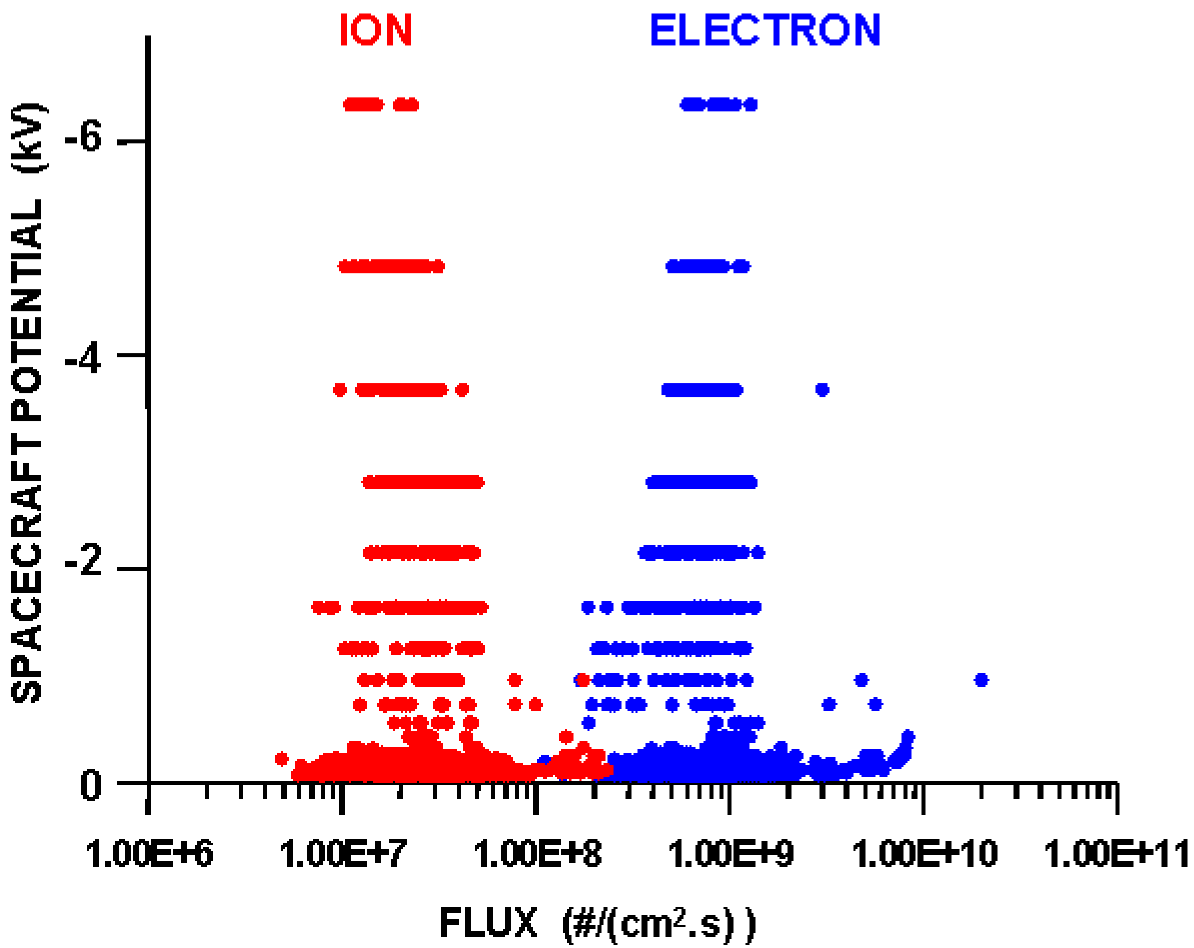


Solar wind compresses the magnetosphere on the day side and elongates it on the night side. The magnetotail snaps back from to time. Energetic plasmas from the magnetotail may reach the geosynchronous altitudes at midnight. Electrons drift to the dawnside. As a result, **spacecraft charging occurs mostly during 0-6 AM.**

Shu T. Lai

ELECTRON AND ION FLUXES
AT GEOSYNCHRONOUS ALTITUDES

(Measurements on LANL-1984, March, Eclipse Periods, 2000)



Lai and Della-Rose [2001]

Shu T. Lai

Why do Spacecraft Charge?

- **Consider a plasma in thermal equilibrium**

$$\frac{1}{2} m_e \mathrm{v}_e^{\,2} = \frac{1}{2} M_i V_i^2$$

- **The electrons are much lighter and faster than the ions**

$$\mathrm{v}_e >> V_i$$

- **Therefore, the flux of electrons is much higher than that of ions**

$$n_e q_e \mathrm{v}_e >> n_i q_i V_i$$

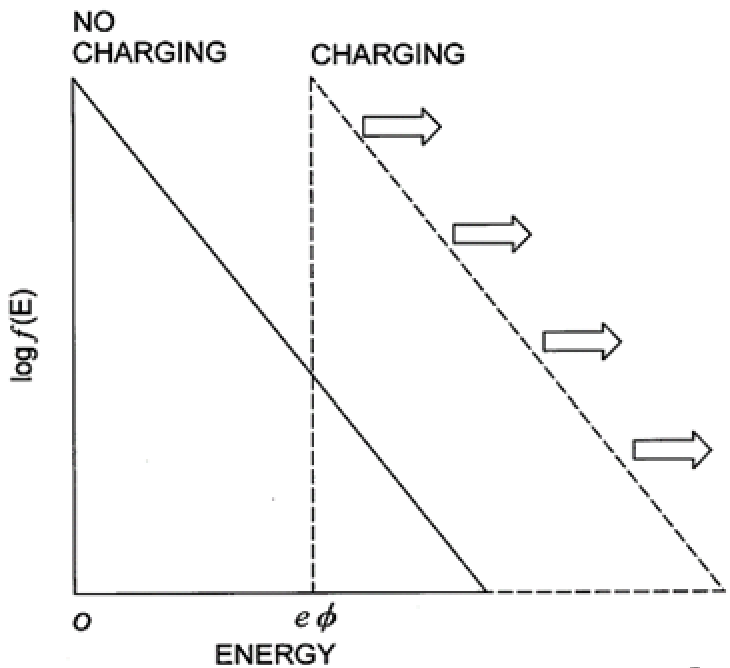
- **This is why spacecraft often charge to negative potentials in a plasma**

- **This is true not only in space but also in the laboratory.**

Measuring Spacecraft (Frame) Potential

$$f(E) = n(m/2\pi kT)^{3/2}\exp(-E/kT)$$

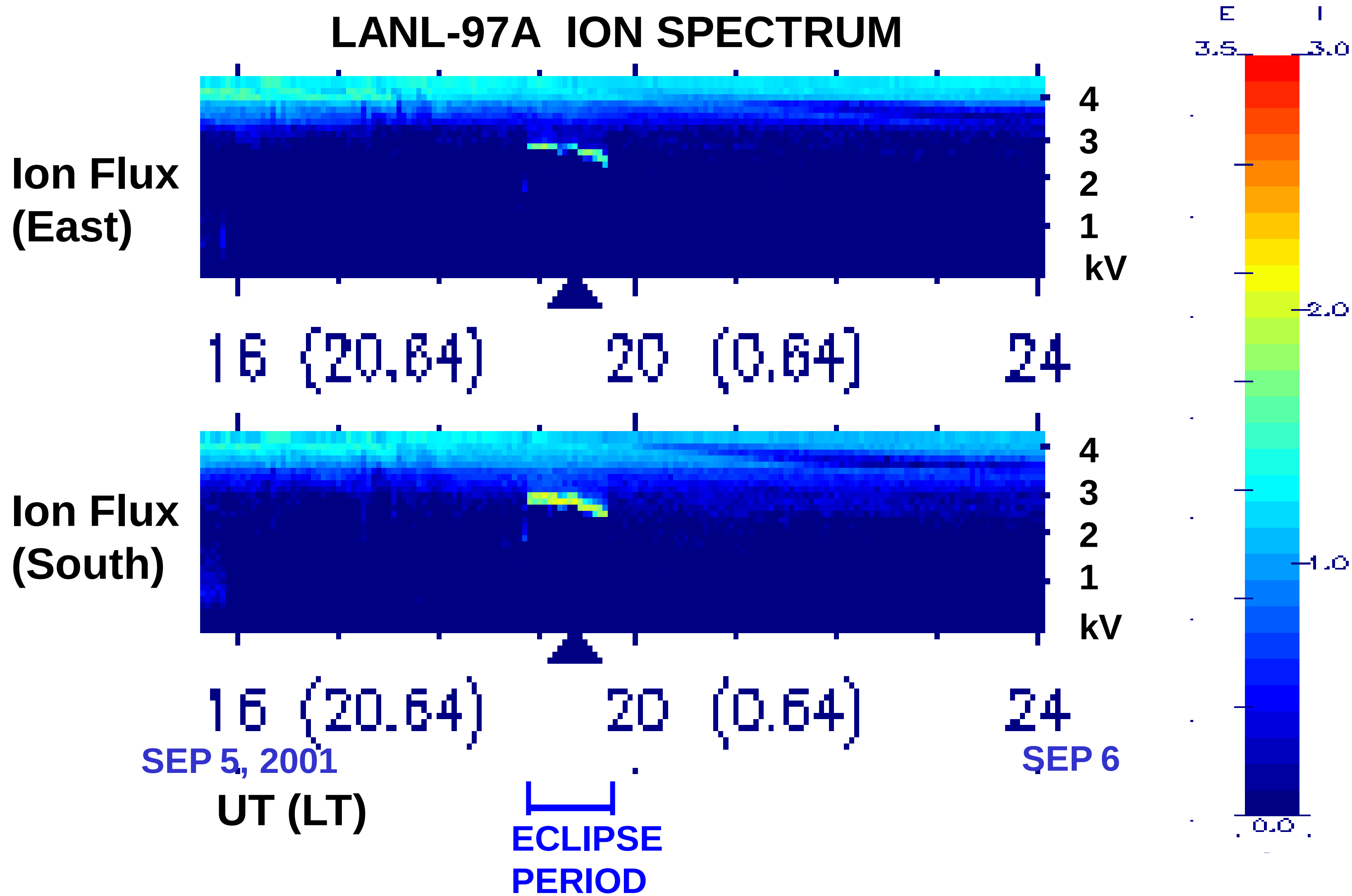
$$\log f(E) = C - E/kT$$



Lai [1998]

- Shift of the energy distribution.
- The shift $e\phi$ gives the charging potential ϕ.

ECLIPSE CHARGING OF LANL-97A TO –3 kV



NOTE: THE ION PEAK INDICATES THE CHARGING VOLTAGE

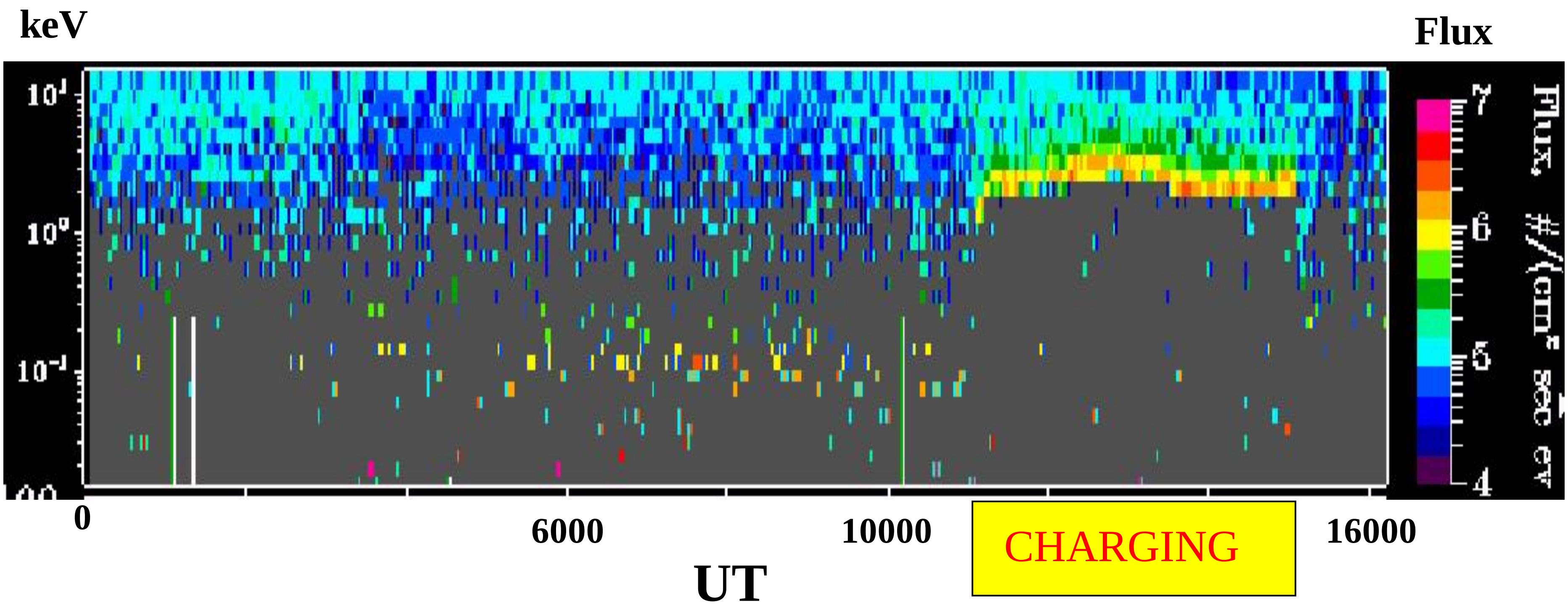
Shu T. Lai

Charging of DSCS

Geosynchronous Satellite

DSCS Satellite

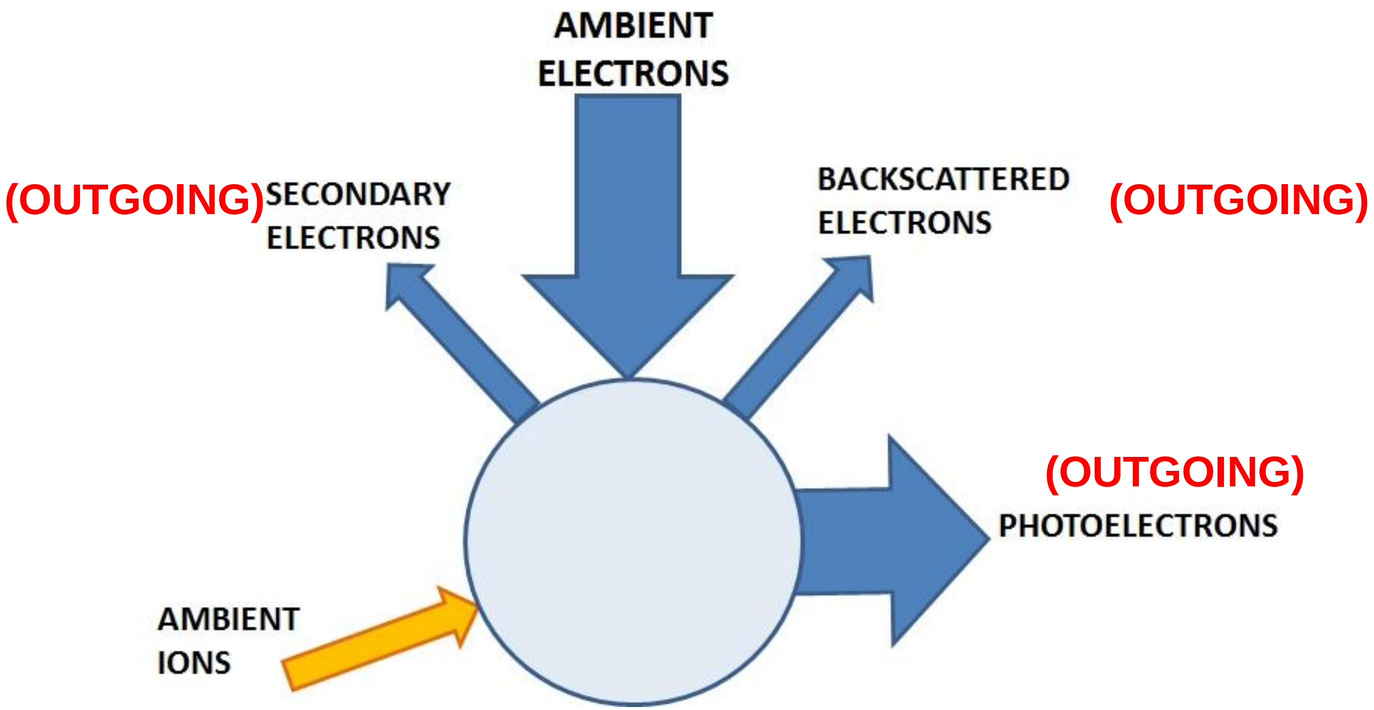
Day 74, 1999



Ambient Ion Flux Spectrum measured on DSCS. Note the ion energy at 2-4 kV during the period of 11000-15000 UT.

Lai [1999]

CURRENT BALANCE



$$I_e - I_i = I_s + I_b + I_{ph}$$

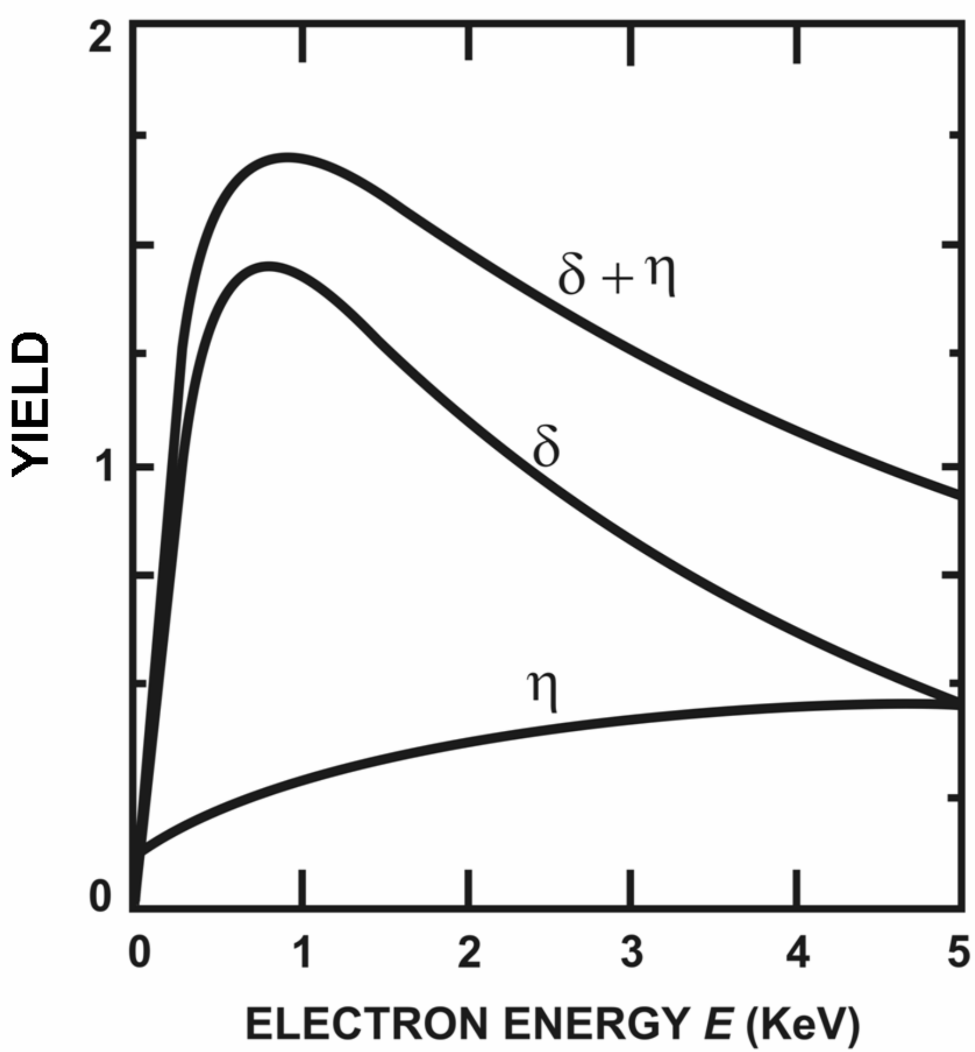
$$\int_0^\infty dE E\, f_e(E) \exp\left(-q_e\phi/kT_e\right) - \int_0^\infty dE E\, f_i(E)\left(1-q_i\phi/kT_i\right)^\alpha = \int_0^\infty dE E\, f_e(E)\left[\delta(E)+\eta(E)\right] + I_{ph}$$

OUTGOING CURRENTS

- Incoming currents can be measured onboard.
- Outgoing currents can hardly be measured.
- To calculate outgoing currents, one needs the yield functions $\delta(E)$, $\eta(E)$, and $Y(\omega)$ for secondary electrons, backscattered electrons, and photoelectrons, respectively.
- Traditionally, one adopts the yield functions from some standard sources, such as materials encyclopedia.
- The functions depend very much on surface conditions!

ELECTRON INDUCED ELECTRONS FROM A SPACECRAFT SURFACE

- Typical secondary electron yield δ(E) and backscattered electron yield η(E).
- δ(E) features a maximum at an energy range of 60 - 2000 eV for typical materials. Beyond the max, it falls monotonically.
- η(E) is much smaller and flatter compared with δ(E).
- The sum, δ(E) + η(E), is the total number of outgoing electrons for an incoming electron of energy E.
- Recent ly (Cimino, 2004) : η(E) rises at below about 20-50 eV and reaches unity at E = 0.



ELECTRON DISTRIBUTION AND SECONDARY EMISSION YIELD

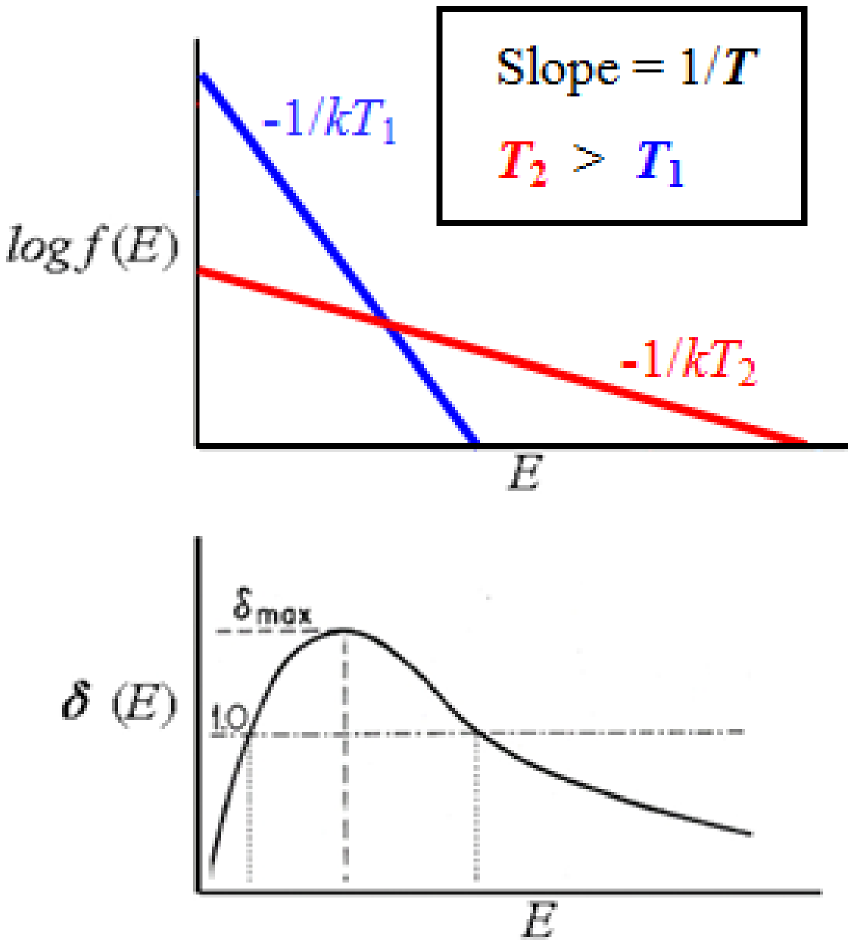


Fig.2 (Upper) Temperature T of a Maxwellian electron distribution. (Lower) Secondary electron coefficient δ as a function of primary electron energy.

- **Imagine 2 camps of electrons.**
- **The low energy camp favors charging to positive voltage, albeit a few V only.**
- **The high energy camp favors charging to negative voltage, which can be -kV.**
- **As temperature increases, there must exist a critical temperature T*, above which the high energy camp wins.**
- **Above T*, negative charging occurs.**

EXISTENCE OF CRITICAL TEMPERATURE *T**

- For studying charging onset, one can ignore the ions because the ion flux is two orders of magnitude lower than that of electrons.

- The Maxwellian distribution function $f(E)$ is a function of E, n, and T

$$f(E) = n(m/2\pi k T)^{3/2} \exp(-E/kT)$$

- Substitute $f(E)$ into the following equation of definite integrals:

$$\int_0^\infty dE\, E\, f(E) = \int_0^\infty dE\, E\, [\delta(E) + \eta(E)]\, f(E)$$

- After the integration over E, the equation is a function of n and T only.

- Since n is a multiplicative factor on both sides of the equation, n cancels out.

- Therefore, the equation is a function of T only. The value T^* of T satisfying this equation is the critical temperature.

- A $\delta(E)$ formula [*Sanders and Inouye*, 1979] is as follows:

$$\delta(E) = c\,[\exp(-E/a) - \exp(-E/b)]$$

where a = 4.3 $E_{\max}$, b = 0.367$E_{\max}$, and c = 1.37 $\delta_{\max}$. The two parameters $E_{\max}$ and $\delta_{\max}$ depend on the surface material.

- An $\eta(E)$ formula [*Prokopenko and Laframboise*, 1980] is as follows:

$$\eta(E) = A - B\exp(-CE)$$

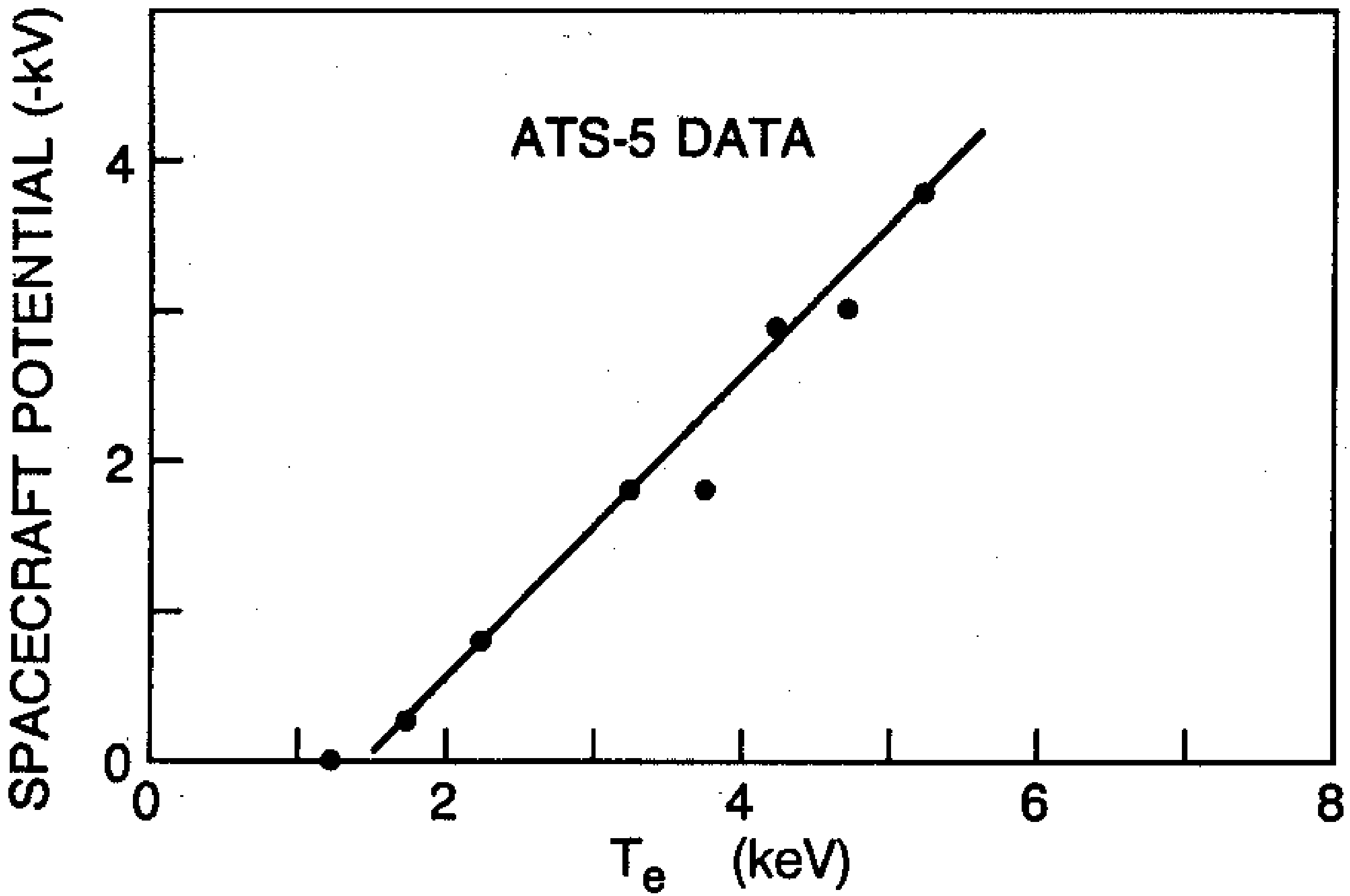
where A, B, and C depend on the surface material.

Onset of Spacecraft Charging
TABLE 1

CRITICAL TEMPERATURE T* (keV)

MATERIAL	ISOTROPIC	NORMAL
Mg	0.4	---
AL	0.6	---
Kapton	0.8	0.5
Al Oxide	2.0	1.2
Teflon	2.1	1.4
Cu-Be	2.1	1.4
Glass	2.2	1.4
SiO_2	2.6	1.7
Silver	2.7	1.2
Mg Oxide	3.6	2.5
Indium Oxide	3.6	2.0
Gold	4.9	2.9
Cu-Be (Activated)	5.3	3.7
MgF_2	10.9	7.8

EVIDENCE OF CRITICAL TEMPERATURE
FOR THE ONSET OF SPACECRAFT CHARGING

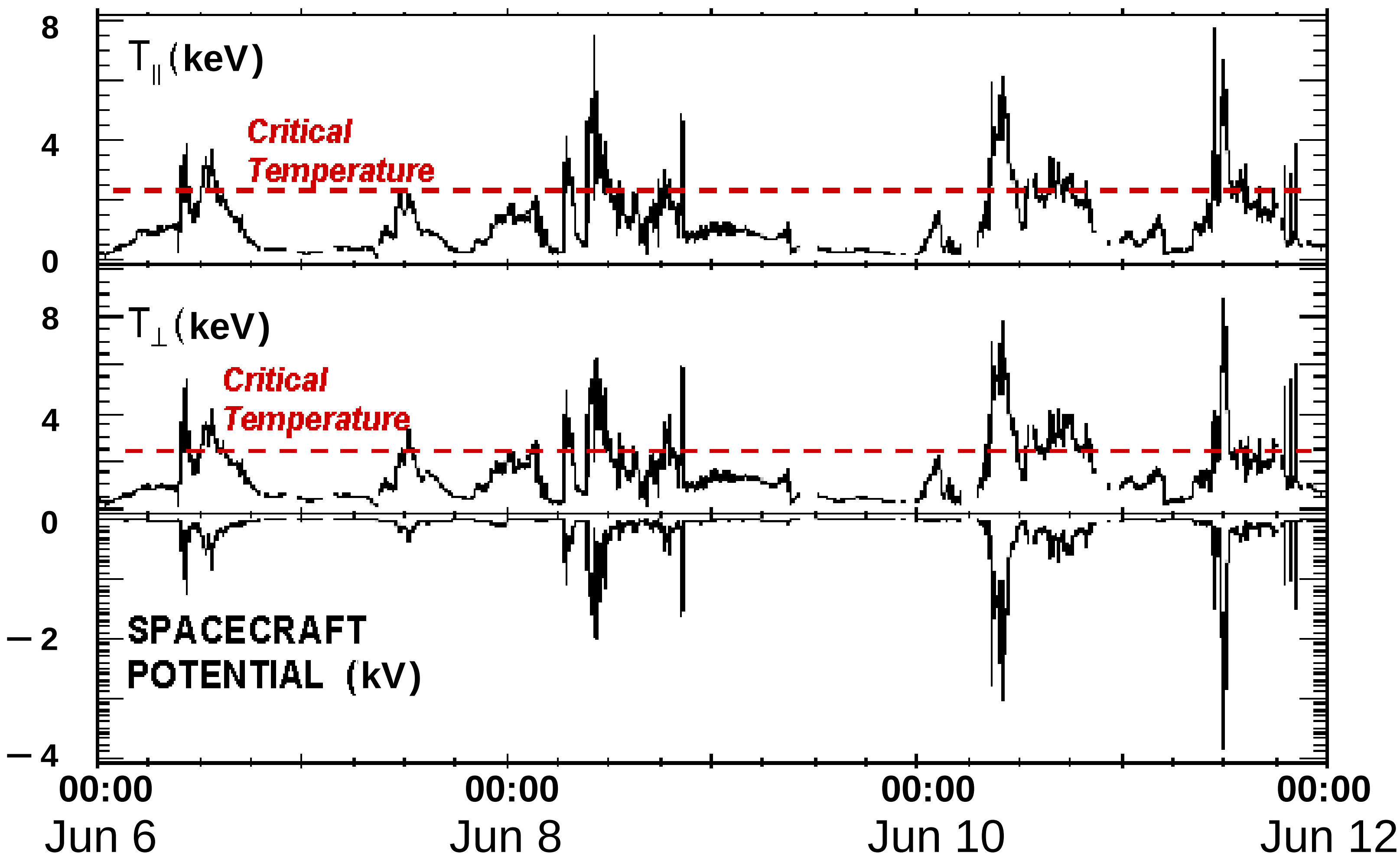


ELECTRON TEMPERATURE

Rubin et al. [1980]

Shu T. Lai

EVIDENCE OF CRITICAL TEMPERATURE
LANL-97A

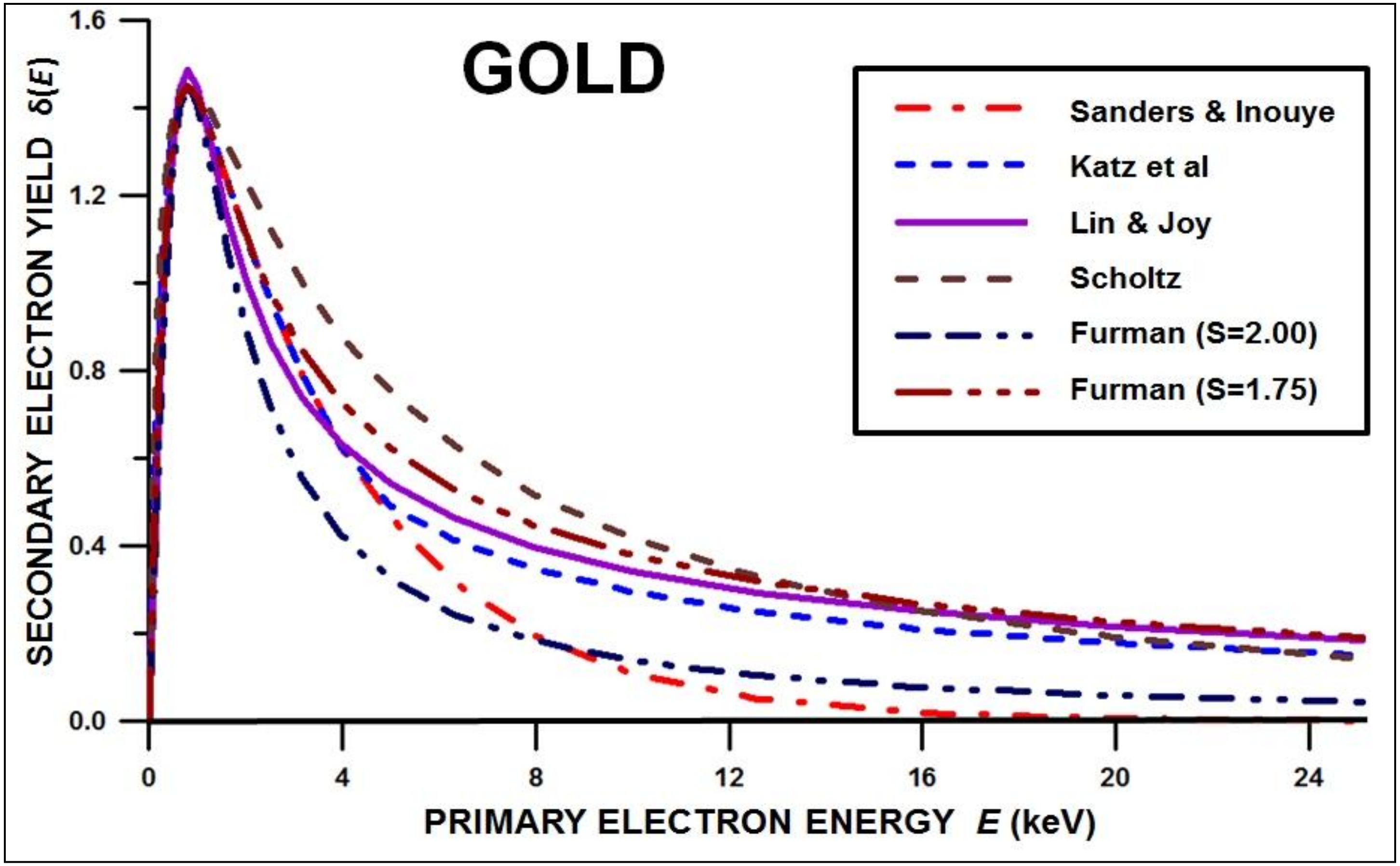


Shu T. Lai

Massachusetts Institute of Technology

SEY δ(E) FORMULAE

Which one is the best?

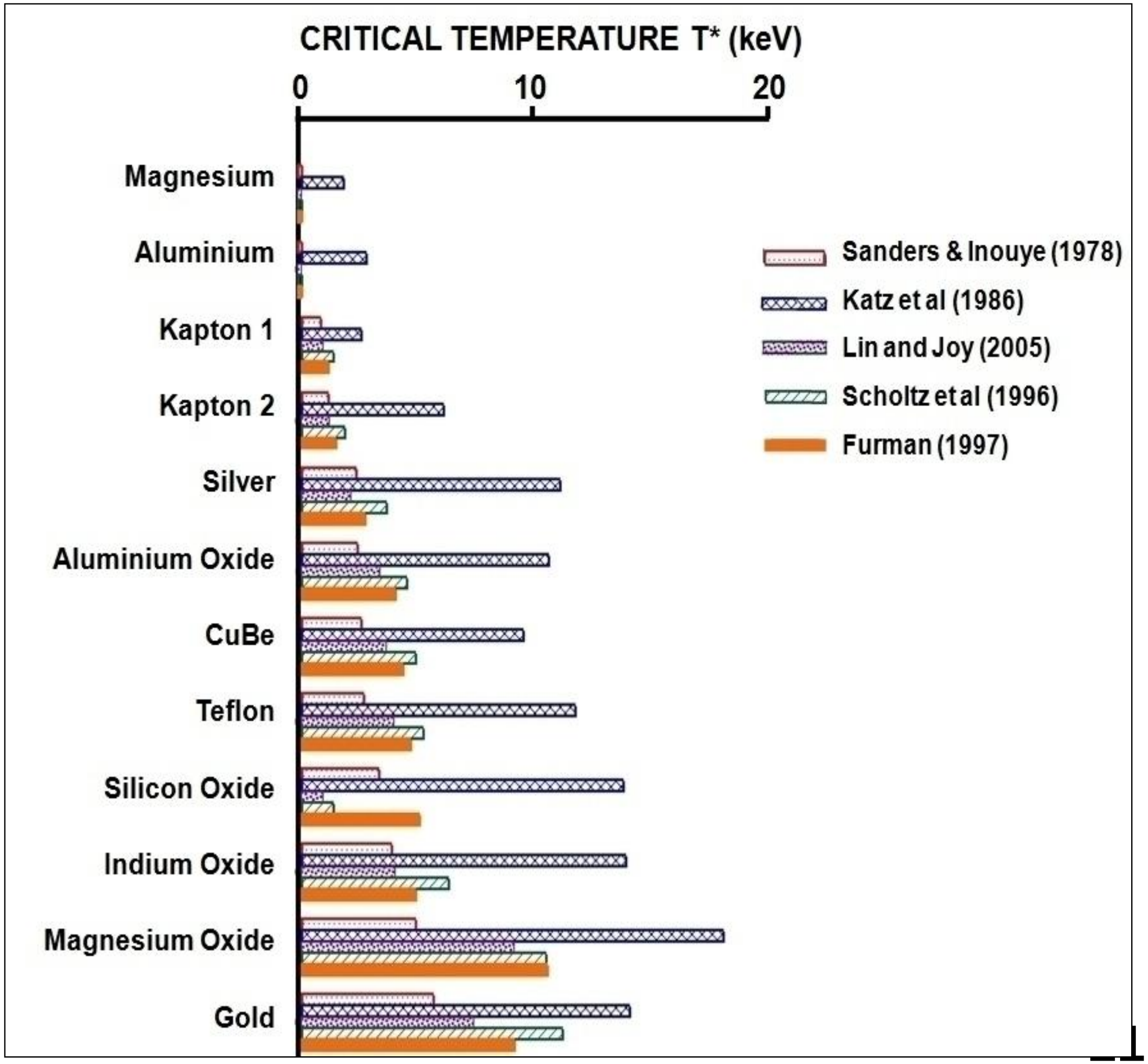


Shu T. Lai

Massachusetts Institute of Technology

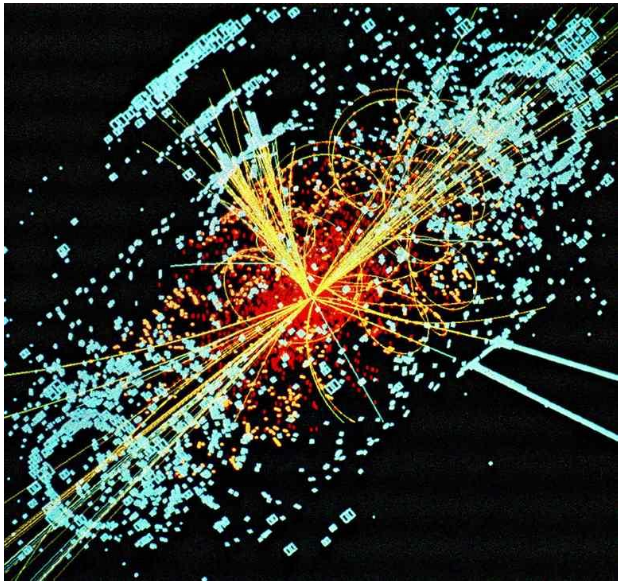
CRITICAL TEMPERATURE

FOR THE ONSET OF SPACECRAFT CHARGING



Shu T. Lai

THE LARGE HADRON COLLIDER (LHC)
CERN, SWITZERLAND

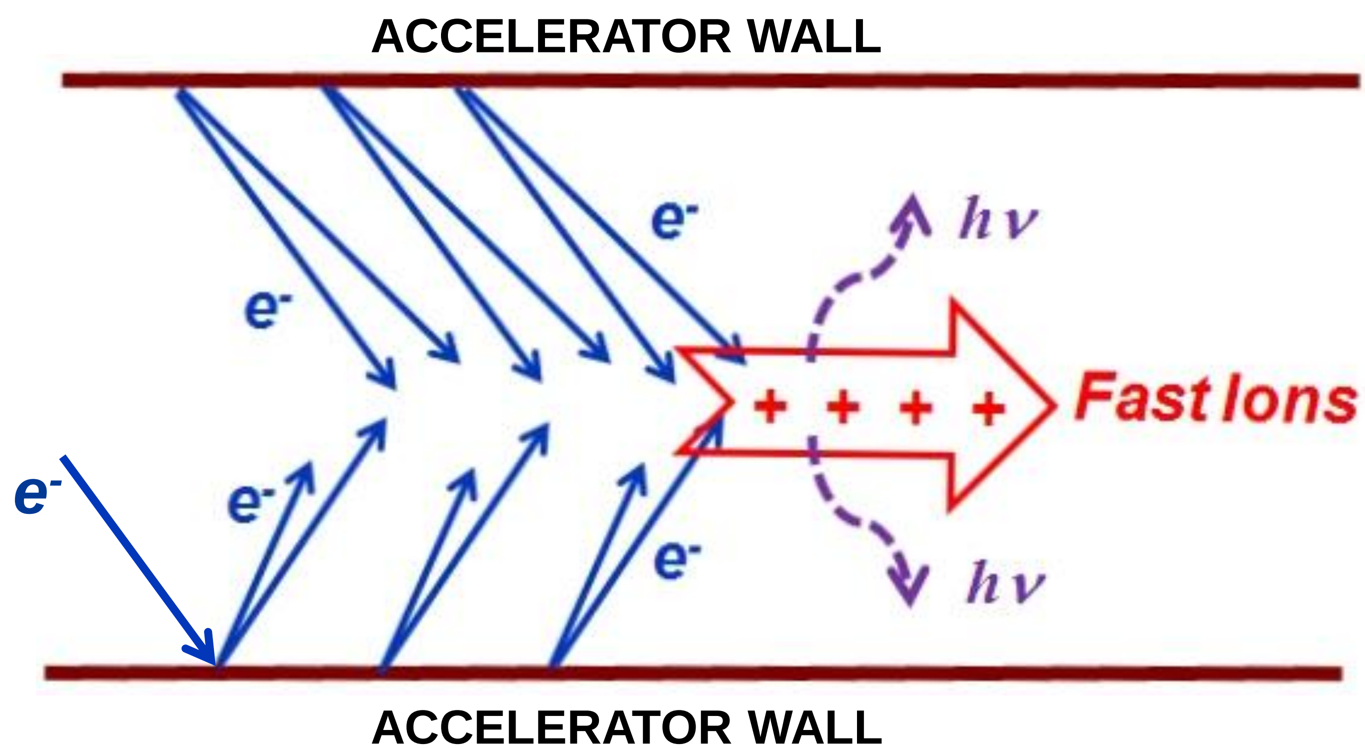


TO STUDY THE BIG BANG OF THE UNIVERSE, HIGG'S BOSON, AND EXTRA DIMENSIONS.

The world's most expensive physics experiments.

The accelerator tubes are miles long.

Requirement - Extremely accurate trajectories of charged particle beams !!



A CERN CONCERN:
Can low energy electron clouds affect fast ion trajectories?

THE SEY δ(E) FORMULA
USED IN LHC, CERN

- **The Furman formula is of the form:**

$$\delta(E,\theta,s)=\delta_{max}(\theta)\frac{s\left(E/E_{max}\right)}{s-1+\left(E/E_{max}\right)^{s}}$$

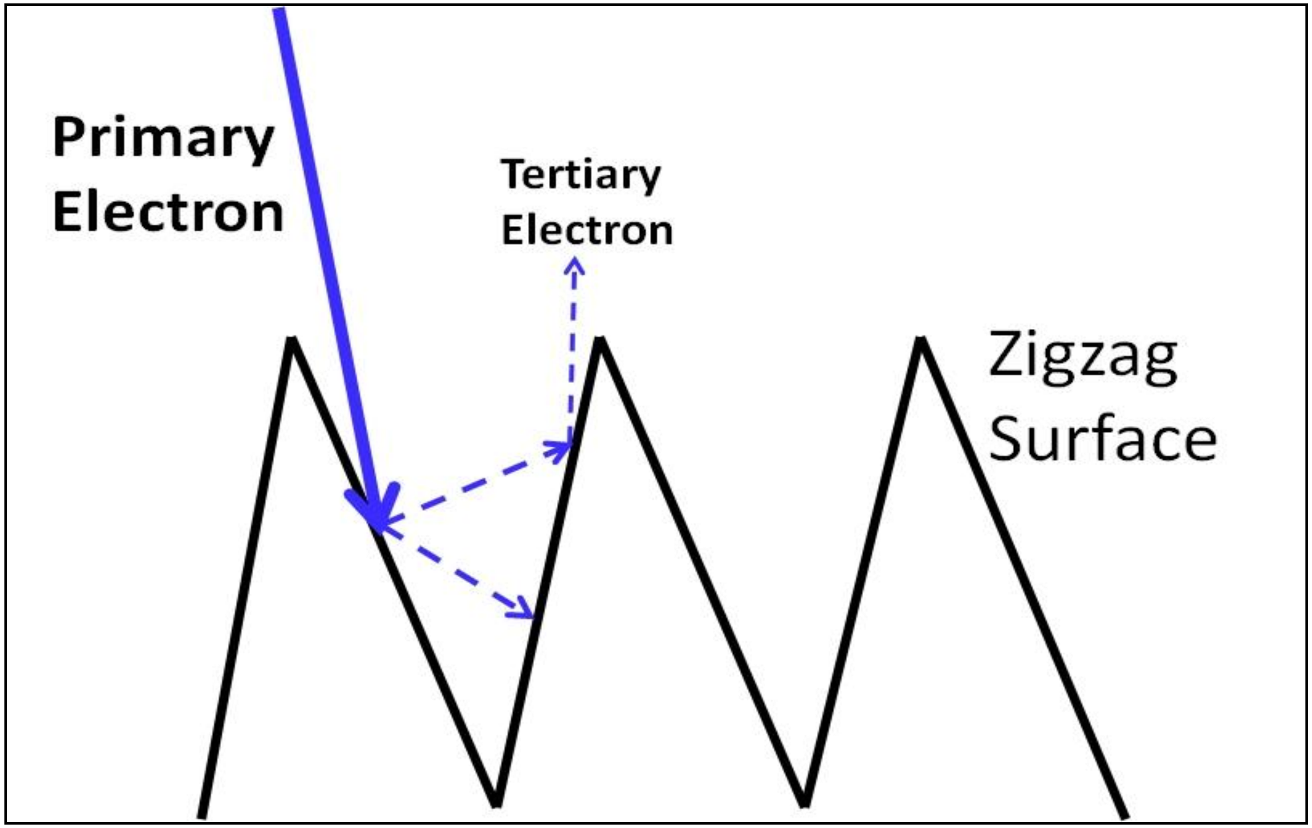
$$\delta_{max}(\theta)=\delta_{max}(0)\exp\left[0.5\left(1-\cos\theta\right)\right]$$

$$E_{max}(\theta)=E_{max}(0)\left[1+0.7\left(1-\cos\theta\right)\right]$$

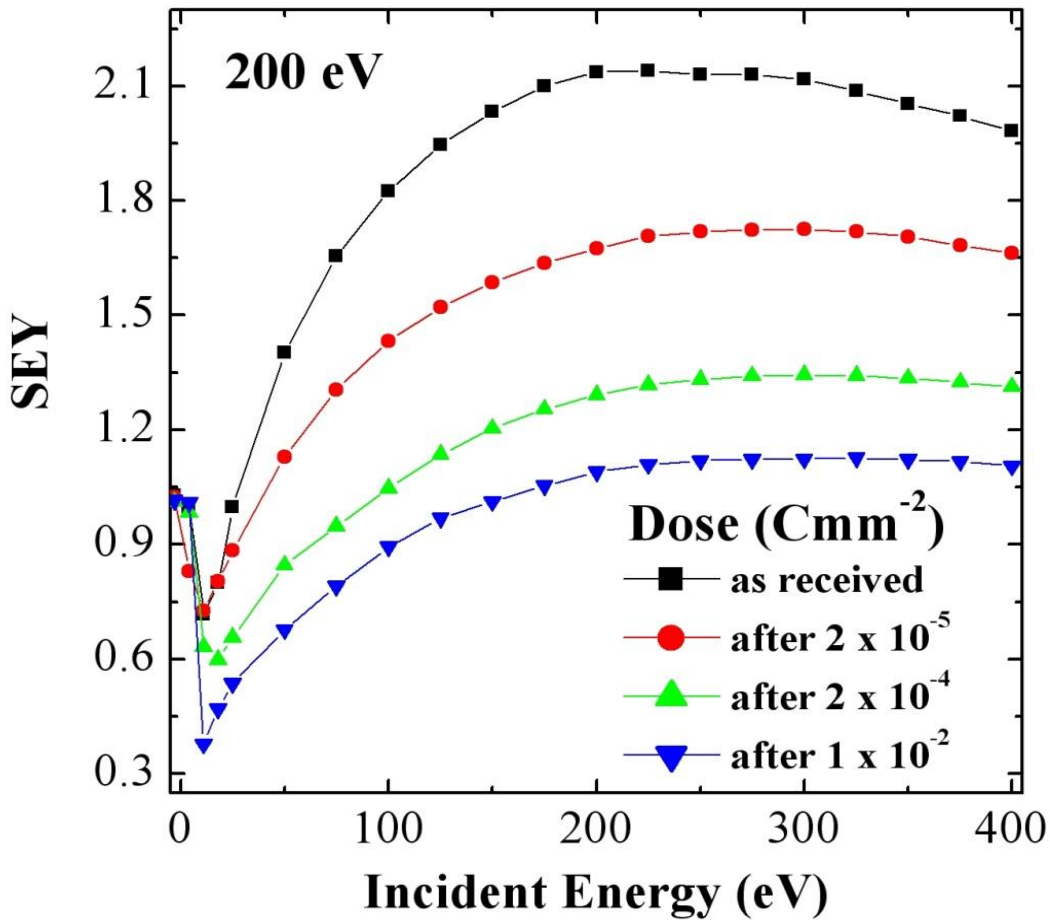
where s, the surface condition parameter, equals 1.35 for the LHC copper samples.

A PEDAGOGICAL EXAMPLE

A saw-tooth surface has low secondary electron yield.



ELECTRON DOSE EFFECT ON $\delta(E)$, RISE OF $\eta(E)$ AT NEAR E=0.



Shu T. Lai

CHARGING OF MIRRORS

- The photoelectron flux emitted from a surface is given by

$$J_{ph}(\omega,\alpha) = J_0(\omega)Y(\omega,\alpha)\left[1 - R(\omega,\alpha)\right]$$

  where J_0 is the incident light intensity at frequency ω and incidence angle α, $Y(\omega, \alpha)$ is the photoelectron yield per absorbed photon, and $R(\omega, \alpha)$ is the reflectance.

- If $R \rightarrow 1$, the photoelectron flux J_{ph} must be small.

- CONJECTURE:

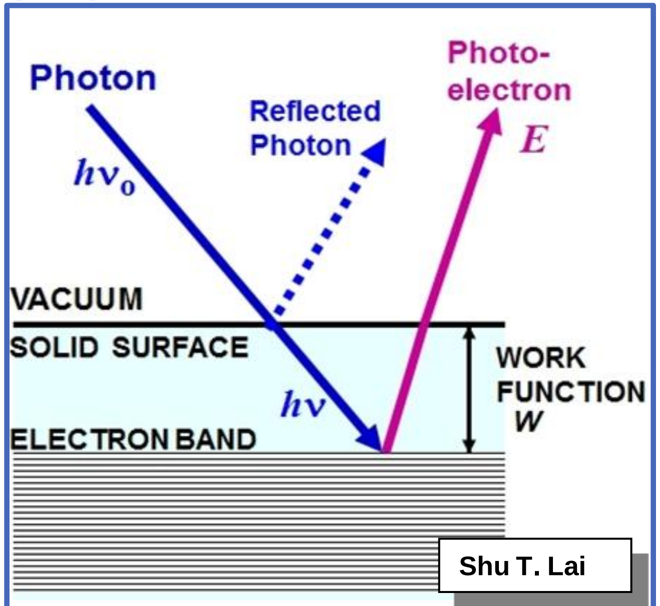
  A mirror should charge in sunlight

  as if it were in eclipse!

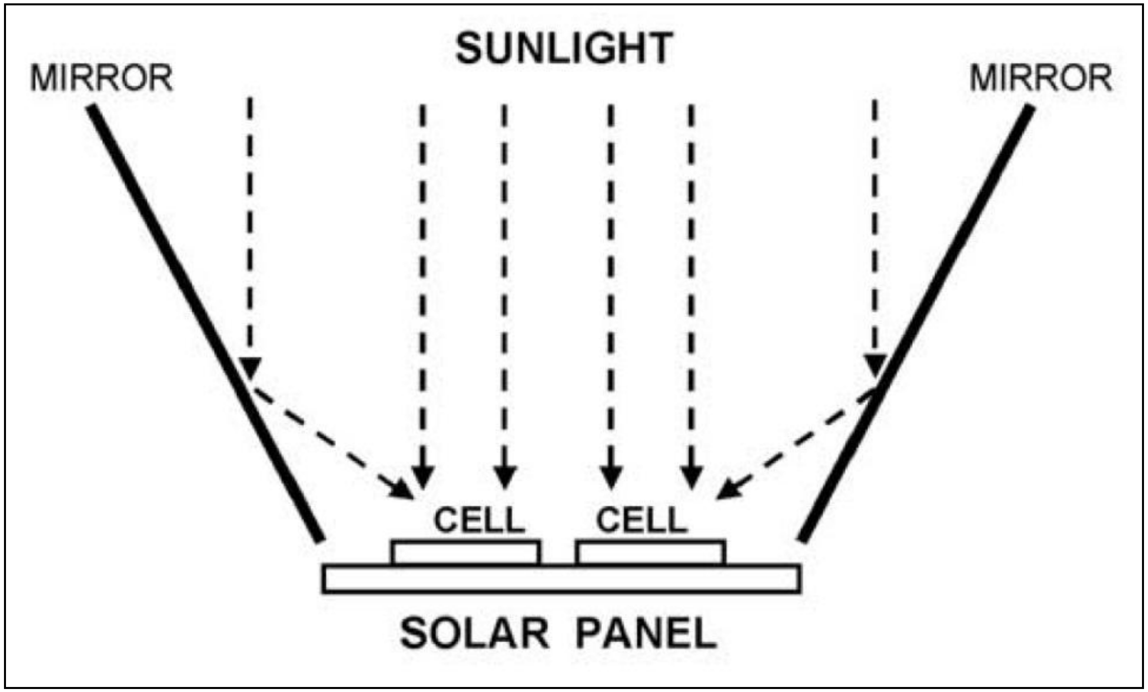
  (Lai, JGR, 110, pp.1104-1115, 2005)

- One should do a laboratory experiment

  to prove or refute this conjecture!



MIRRORS FLANKING SOLAR CELLS

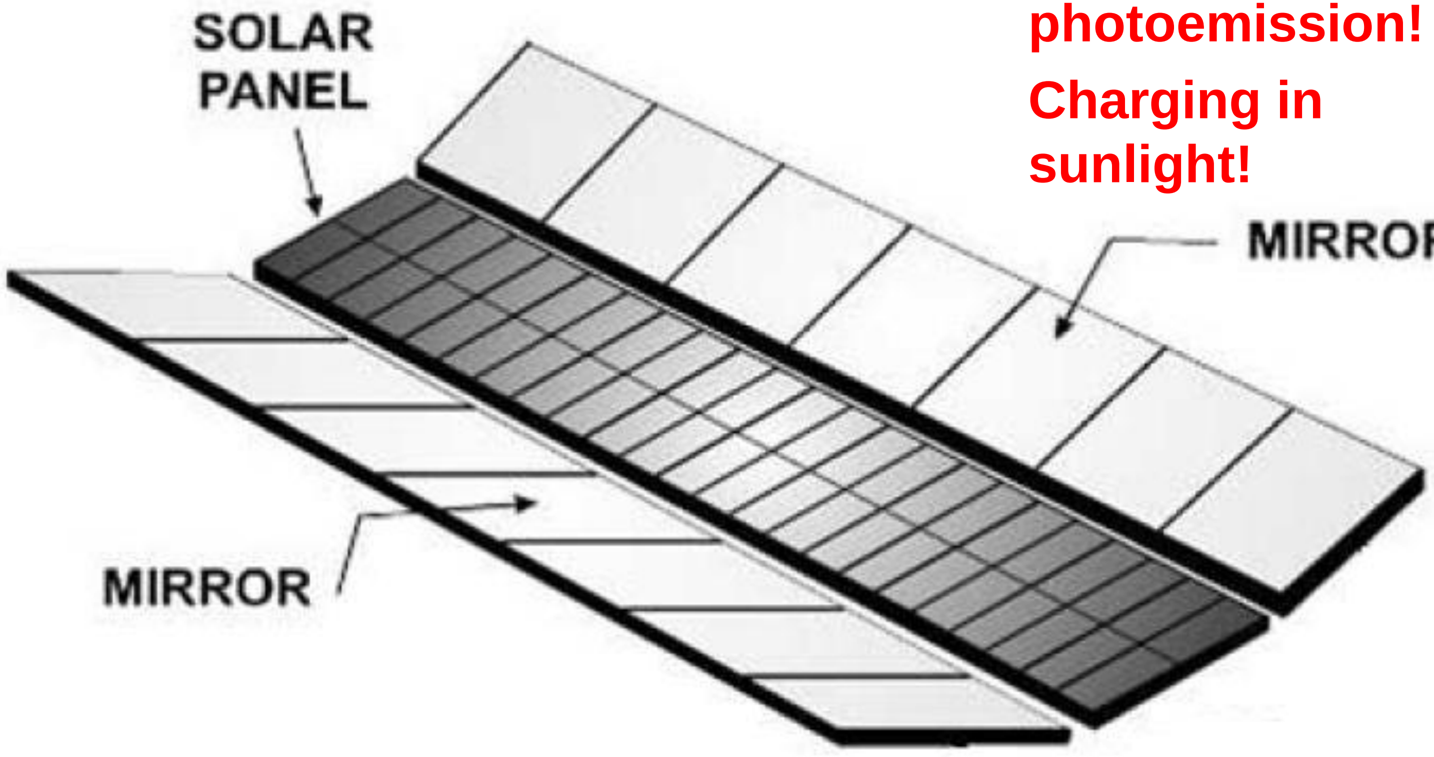


MIRRORS FLANKING SOLAR CELLS
A Differential Charging Hazard

Photoemission suppresses charging

No photoemission!

Charging in sunlight!



CONCLUSIONS

- SPACECRAFT CHARGING AFFECTS SCIENTIFIC MEASUREMENTS ONBOARD.
- CURRENT BALANCE GOVERNS THE SPACECRAFT POTENTIAL.
- CRITICAL TEMPERATURE T* CONTROLS THE ONSET OF SPACECRAFT CHARGING.
- INCOMING CURRENTS CAN BE MEASURED; OUTGOING CURRENTS ARE CALCULATED USING THE YIELD FUNCTIONS.
- THE YIELD FUNCTIONS DEPEND ON THE TYPE OF MATERIAL, PRIMARY ELECTRON ENERGY, INCIDENCE ANGLE, AND SURFACE CONDITIONS SUCH AS ROUGHNESS, DOSE, MONOLAYERS.
- REFLECTANCE AFFECTS PHOTOELECTRON YIELD.
- REFLECTIVE SURFACES CHARGE IN SUNLIGHT AS IF IN ECLIPSE.
- SOLAR PANEL FLANKED BY MIRRORS IS A HAZARDOUS SITUATION.

Massachusetts Institute of Technology

REFERENCES

Cimino, R., et al., *Phys. Rev. Lett*., 93, No.1, 2004, pp.14801-14804.

Cimino, R., *Nucl. Instr. Methods Phys. Res. A*, No.561, pp.272-275, 2006.

Cimino, R., et al., Electron energy dependence of scrubbing efficiency to mitigate e-cloud formation in accelerarors, Proc. EPAC08, Genoa, Italy, 2008.

Furman, M. et al., MBI 97 Tsukuba, KEK 97-17, 1997.

Lai, S.T., *IEEE Trans. Nucl. Sci*., **19**, 1991, 1629-1634.

Lai, S.T. and D. Della-Rose, *J. Spacecraft & Rockets*, **38**, 922-928, 2001.

Lai, S.T. and M. Tautz, *IEEE Trans. Plasma Sci*., **34**, No.5, 2053 - 2061 2006.

Lai, S.T. (ed.), Spacecraft Charging, AIAA, NY, 2012.

Prokopenko, S.M. and Laframboise J.G.L., *J. Geophys. Res*., **85**, No.A8,.4125-4131, 1980.

Sanders, N.L. and G.T.Inouye, in *Spacecraft Charging Technology*, R.C.Finke and C.P. Pike, ed., 747-755, NASA-2071, ADA ADA-084626, 1978.

Whipple, E.C., *Reports on Progress in Physics*, **44**, 1197-1250, 1981.

Massachusetts Institute of Technology

ECLOUD'12

ACKNOWLEDGMENT

The Los Alamos Magnetospheric Plasma Analyzer (MPA) measurements were obtained from the CDAWeb data service at NASA Goddard Space Flight Center.