Environmental effects - III (plasma)

Lecture 9

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Space Environment Technologies

Announcements

Contributions

- ***Lecture 8 items of interest***
  - **"Will Compasses Point South?"** (*NYT* article) at DEN site (Supplemental materials folder) - interesting article about the coming polar reversal and implications for likely space environment effects, including increased radiation from solar storms at low altitudes and latitudes due to a weakened magnetic field
  - **Movement of Earth Magnetic** http://www.youtube.com/watch?v=86mjg4qW6tw&feature=related
  - **Earth Magnetic Field Reversal** - energy ramifications of diminishing magnetic field - how long will it linger at zero before reversing? http://pureenergysystems.com/news/2005/02/27/6900064_Magnet_Pole_Shift/
  - **Dst availability - ring current index** http://sol.spacenvironment.net/~maps/
  - **Dst forecast:** http://sol.spacenvironment.net/~sam_ops/Index.html

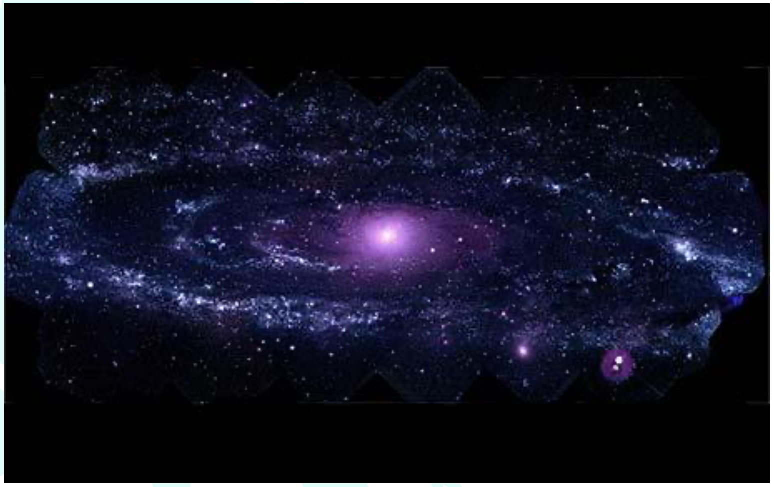
Announcements

Contributions

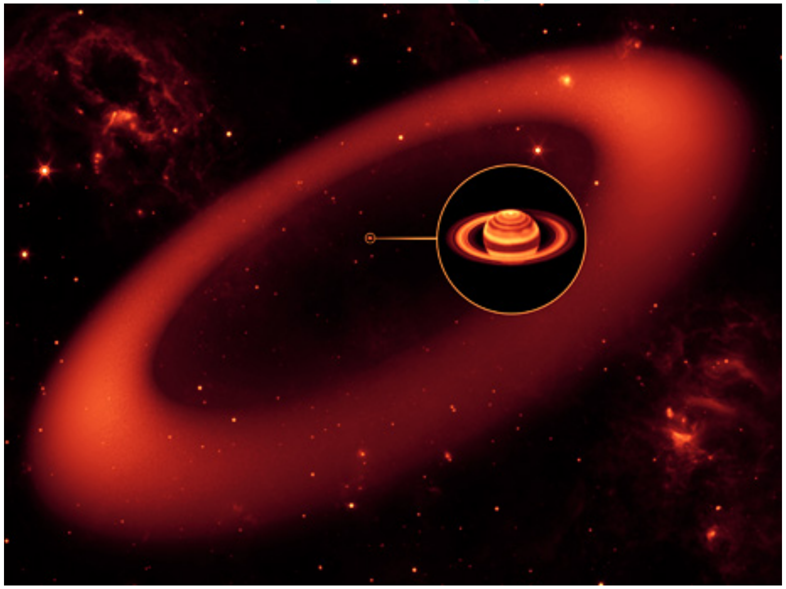
- **PC Fortran compilers -** http://www.thefreecountry.com/compilers/fortran.shtml
- Meteor burning up in Earth's atmosphere video http://link.brightcove.com/services/link/bcpid1513658585/bctid1877516013 and article at http://www.space.com/scienceastronomy/081024-fireball-meteorite.html
- substorm animation http://svs.gsfc.nasa.gov/vis/a010000/a010100/a010104/index.html
- solar magnetic fields and Earth http://www.space.com/scienceastronomy/081103-mm-magnetic-portals.html
- potentially habitable planet: Gliese 581g orbiting a star 20 light years away from Earth: http://www.nasa.gov/topics/universe/features/gliese_581_feature.html
- Kepler observatory researchers estimate there are 11-40 billions Earths in the Milky Way Galaxy.

Contributions

1) Articles about the best up to date picture of the Andromeda galaxy, by the Swift satellite:
   - http://migre.me/s/8rgq
   - http://www.telegraph.co.uk/science/space/6335258/Andromeda-galaxy-Nasa-Swift-Satellite-takes-best-ever-picture.html



2) An enormous ring has been found around the planet Saturn:
   - http://news.nationalgeographic.com/news/2009/10/091007-new-saturn-ring-largest.html
   - http://blogcritics.org/scitech/article/newly-discovered-saturn-ring-dwarfs-all/
   - http://www.google.com/hostednews/afp/article/ALeqM5jkJv2jxriagrRxiClO9CIppkBbYw



3) Mysterious space ribbon found at the edge of the solar system by the IBEX spacecraft:
   - http://www.world-science.net/othernews/091015_ibex.htm
   - http://www.tgdaily.com/content/view/44321/184/

Opportunity at Mars imaged by MRO

Credit: NASA

Contributed sites on magnetosphere

1) http://library.advanced.org/15215/media/magsphrqsmf.MOV (nice cartoon movie)
2) http://radbelts.gsfc.nasa.gov/outreach/RadMovies.html (magnetic storm) http://radbelts.gsfc.nasa.gov/movies/mp_trace_sm.mpg http://radbelts.gsfc.nasa.gov/movies/me_trace_sm.mpg
3) http://pwg.gsfc.nasa.gov/istp/news/9812/solarmovies.html (second movie) http://pwg.gsfc.nasa.gov/istp/news/9812/plasma.mov
4) http://istp.gsfc.nasa.gov/istp/news/0005/movies.html (third movie on this page) http://istp.gsfc.nasa.gov/istp/news/0005/final3.mov

Announcements

Contributions

- How Mars lakes may have once developed: http://www.physorg.com/news/2010-10-martian-lakes-seas-emerging-underground.html
- Stars that formed 200 light years ago: http://www.physorg.com/news/2010-10-image-stars-born.html
- Here's a picture that was featured on APOD of the comet (which is green!). http://antwrp.gsfc.nasa.gov/apod/ap101007.html
- NASA Space Exploration Act. Here is a link: http://www.space.com/news/nasa-obama-new-direction-faq-100624.html
- COORDINATING EFFORTS TO PREPARE THE NATION FOR SPACE WEATHER EVENTS Executive order. Here is a link: https://www.federalregister.gov/documents/2016/10/18/2016-25290/space-weather-events-coordinating-efforts-to-prepare-the-nation-eo-13744
- **PROSWIFT space weather bill signed into law: https://spacewx.com**

Announcements

Contributions

- ***Lecture 9 items of interest***
  - An in depth "non-mathematical" tutorial on the Earth's magnetosphere by David P. Stern and Mauricio Peredo, with links to other sites as well: http://www-istp.gsfc.nasa.gov/Education/Intro.html
  - "A Beginner's Guide to the Earth's Magnetosphere" by the American Geophysical Union (AGU): http://www.agu.org/sci_soc/cowley.html
  - NASA's Cosmicopia website, with good information on the basics of the magnetosphere as well as links to several interesting recent articles in the news: http://helios.gsfc.nasa.gov/magnet.html

Aurora over Michigan

Credit: NASA

Lecture Overview

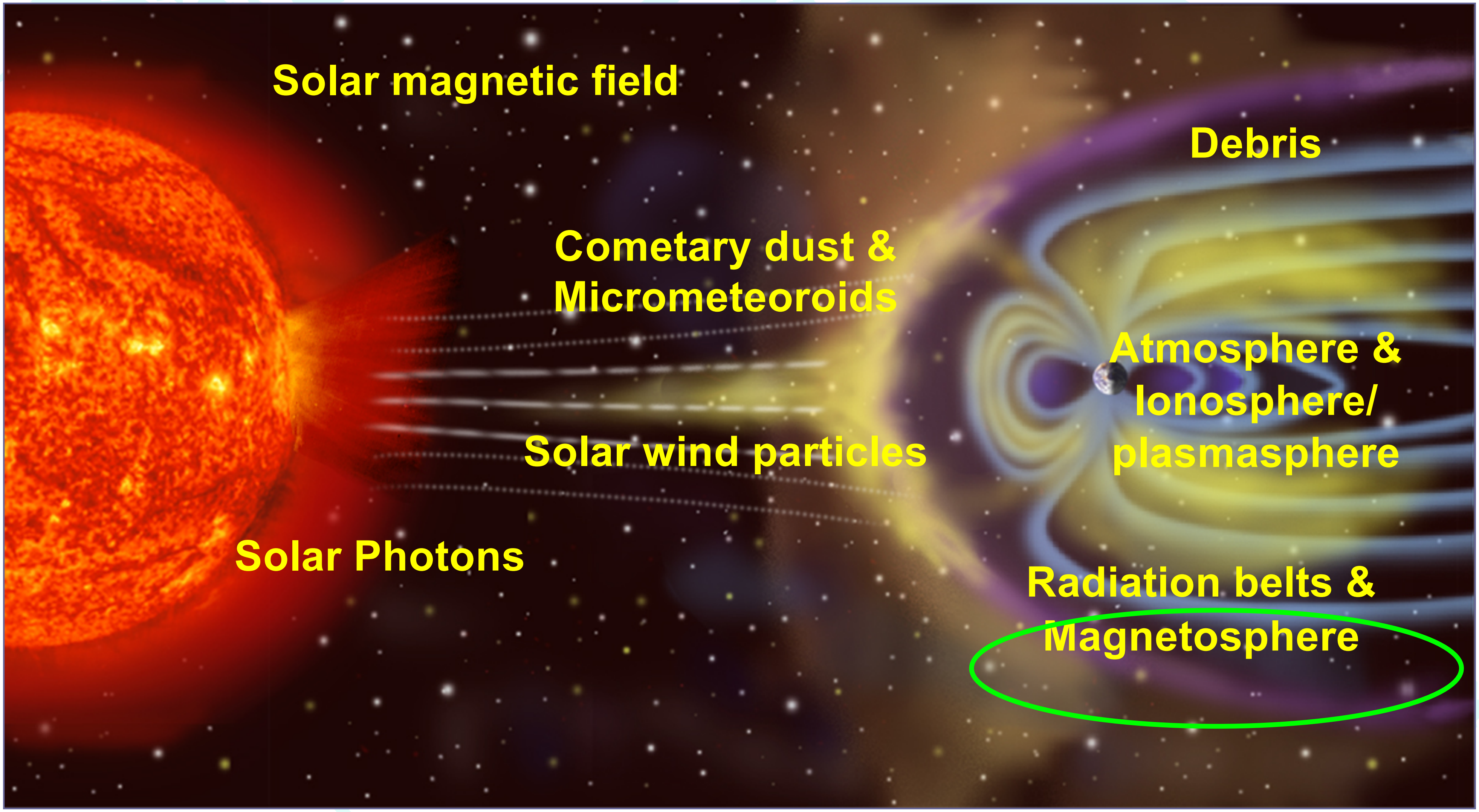
Environmental effects (plasma)

- Plasma effects
  - Electron and ion surface interactions, current collection
- Spacecraft charging
  - Sources of charging
    - Photoelectric effect, plasma bombardment, discharge
  - LEO charging
    - Unbiased, biased (solar arrays), grounding, within auroras, field aligned currents
  - High altitude charging
    - GEO, SCATHA
- Results of charging - electrostatic discharge (ESD)
  - Paschen discharge and arcing
- Design considerations
  - Materials selection and plasma contactors
- Resources

Homework

The planetary space environment

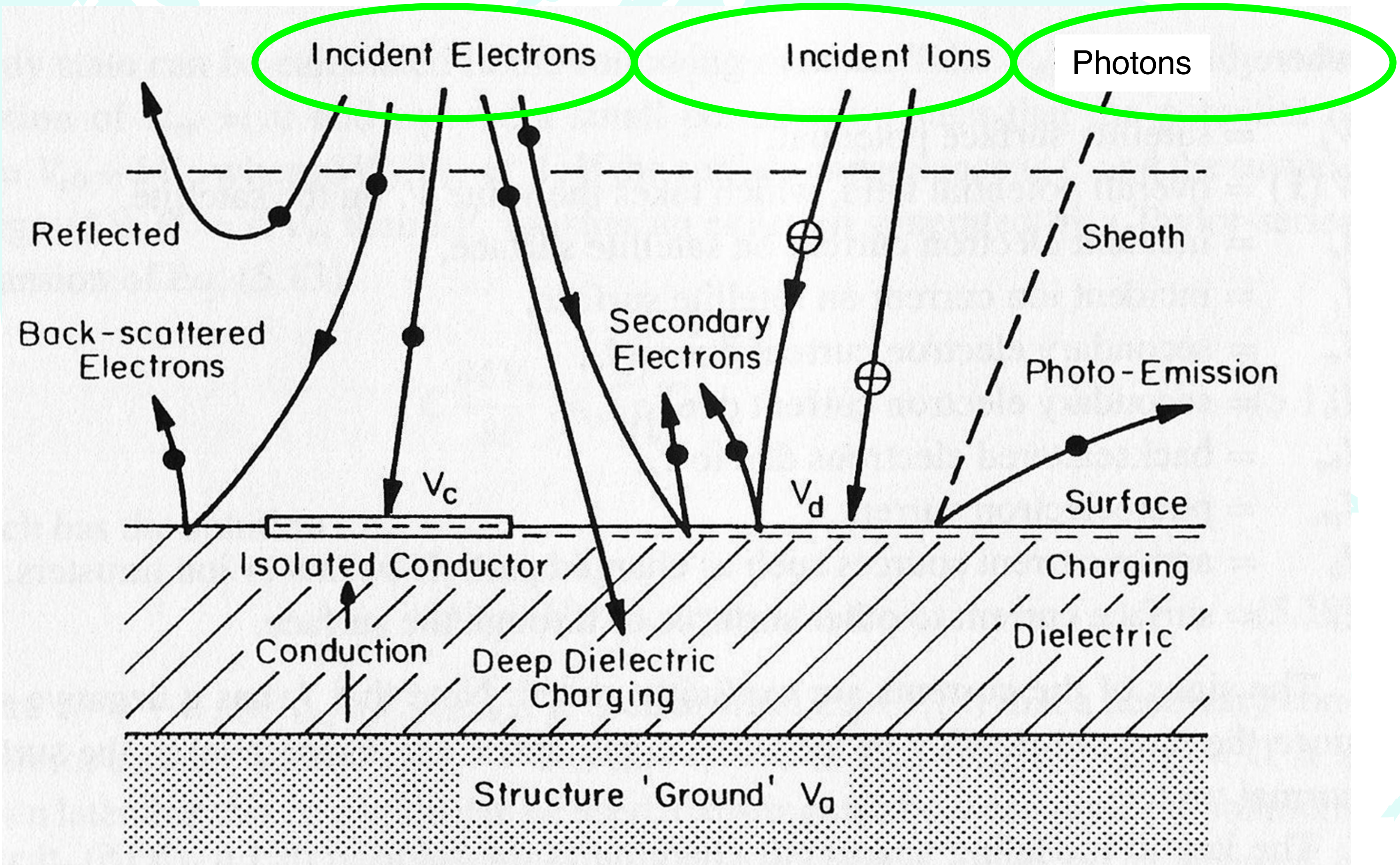
The space environment



Credit: Steele Hill/NASA

Plasma effects

Surface interactions



Credit: Garrett

Plasma - surface interactions

Charged particle - surface interactions

- **Electron and ion** impacts differ from **neutral particle and photon** interactions
  - Typically more energetic impacts than neutrals
  - Charged particles can be affected by electromagnetic forces around the spacecraft (EM forces can attract or repel particles)
  - Mass of particle also affects interactions with spacecraft surface

Credit: Ketsdever

Electron - surface interactions

Interaction process - desorption (augering)

- High energy electrons act with surface species, remove inner core electrons, and result in energy level transitions that lead to desorption (*removal or evaporation*)
- Does not happen with low energy electron impact
- Local heating occurs along with evaporation
- Small effect on bulk particles from a metal
- Large effect of removing monolayer contaminants from metal surfaces

Credit: Ketsdever

Electron - surface interactions

Interaction process - sputtering (atomic and ionic species)

- Electron bombardment preferentially sputters (removes) oxygen from oxide layers
- Not a steady process - as bombardment continues, more metal is exposed and the number of sputtered (removed) particles decreases
- Oxide layers reduce with time and pure metal surfaces increase with time
- Yield of ~10^{-5} or 10^{-6} atoms per electron impact (not efficient - heavier atomic species have much greater mass than the electron)

Credit: Ketsdever

Electron - surface interactions

Interaction process - formation of secondary electrons

- Electrons are most important process and very efficient at producing secondary electrons from surfaces
- Yield of secondary electrons, δ, is defined as the average number of **external electrons** produced per incident electron
- The true yield, δ_t, is the average number of electrons produced **from the surface** per incident electron
- The backscattering coefficient, η, is defined as the average number of **incident electrons** scattered from the surface. Therefore,

$$\delta = \delta_t + \eta \qquad \textbf{(9-1)}$$

- Most data on secondary electron emission is given in terms of δ rather than δ_t

Credit: Ketsdever

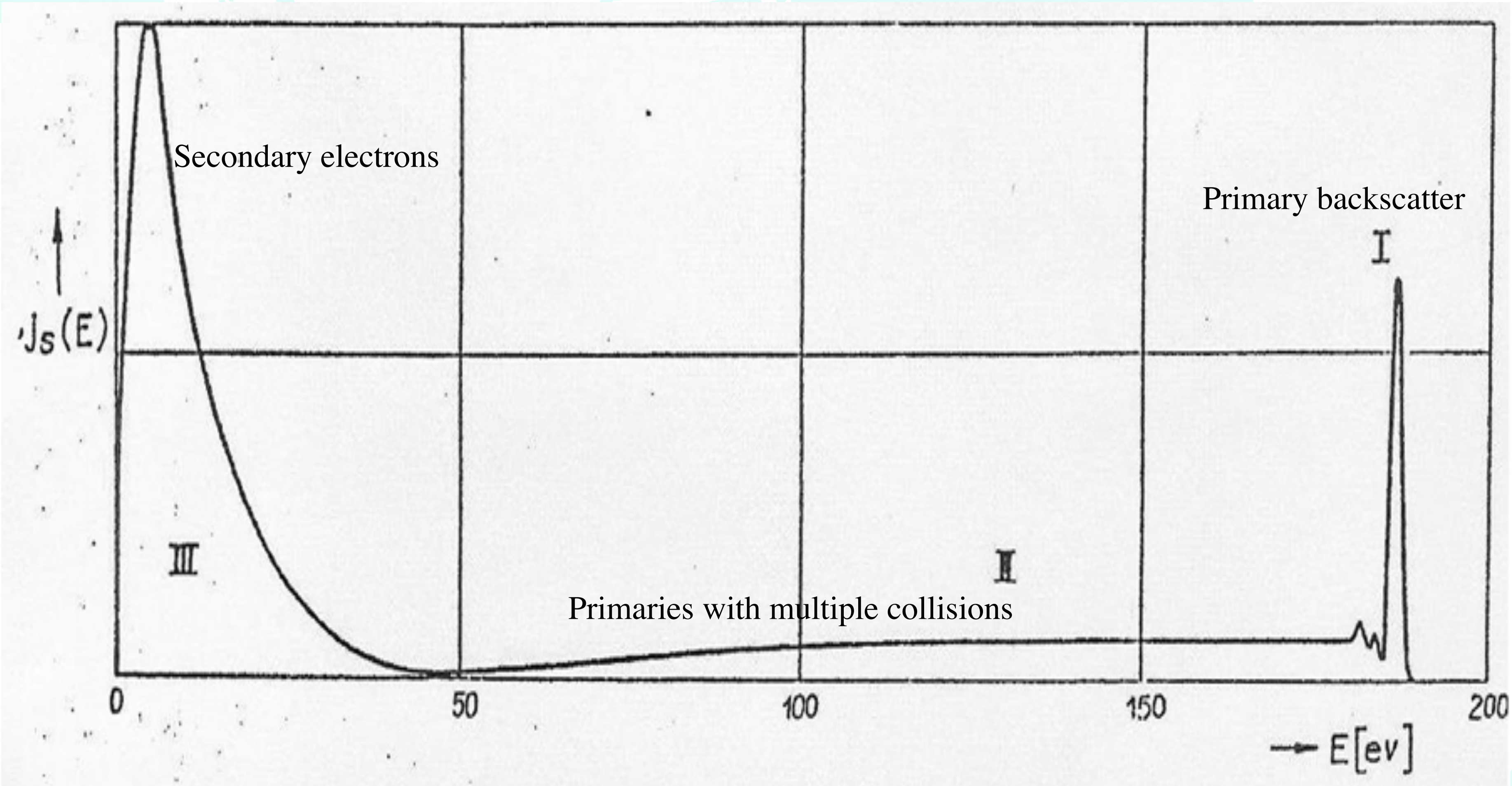
Electron - surface interactions

Secondary electron yields

- Three distinct regions for energy distribution of secondary electrons
- Region I - same energy as primary (incident) electrons) (Ep) and these are basically elastic backscattered electrons from the surface
- Region II - few true secondaries but mainly primary electrons that have participated in multiple collisions at the surface
- Region III - the true secondary electrons with energies around a few electron volts

Credit: Ketsdever

Electron - surface interactions



Credit: Ketsdever

Electron - surface interactions

Typical secondary electron yield

- Secondary electron yield, δ, varies with the primary electron energy
- At low incident energy, few secondaries are ejected since energy tends to be less than the work function at the surface and they cannot escape
- At intermediate incident energy, many secondaries are ejected and can exceed unity
- At high incident energy, most secondaries are produced deep within the material; they lose energy via collisions before the reach the surface and also do not escape
- Secondary electron production depends also on surface roughness and contamination

Credit: Ketsdever

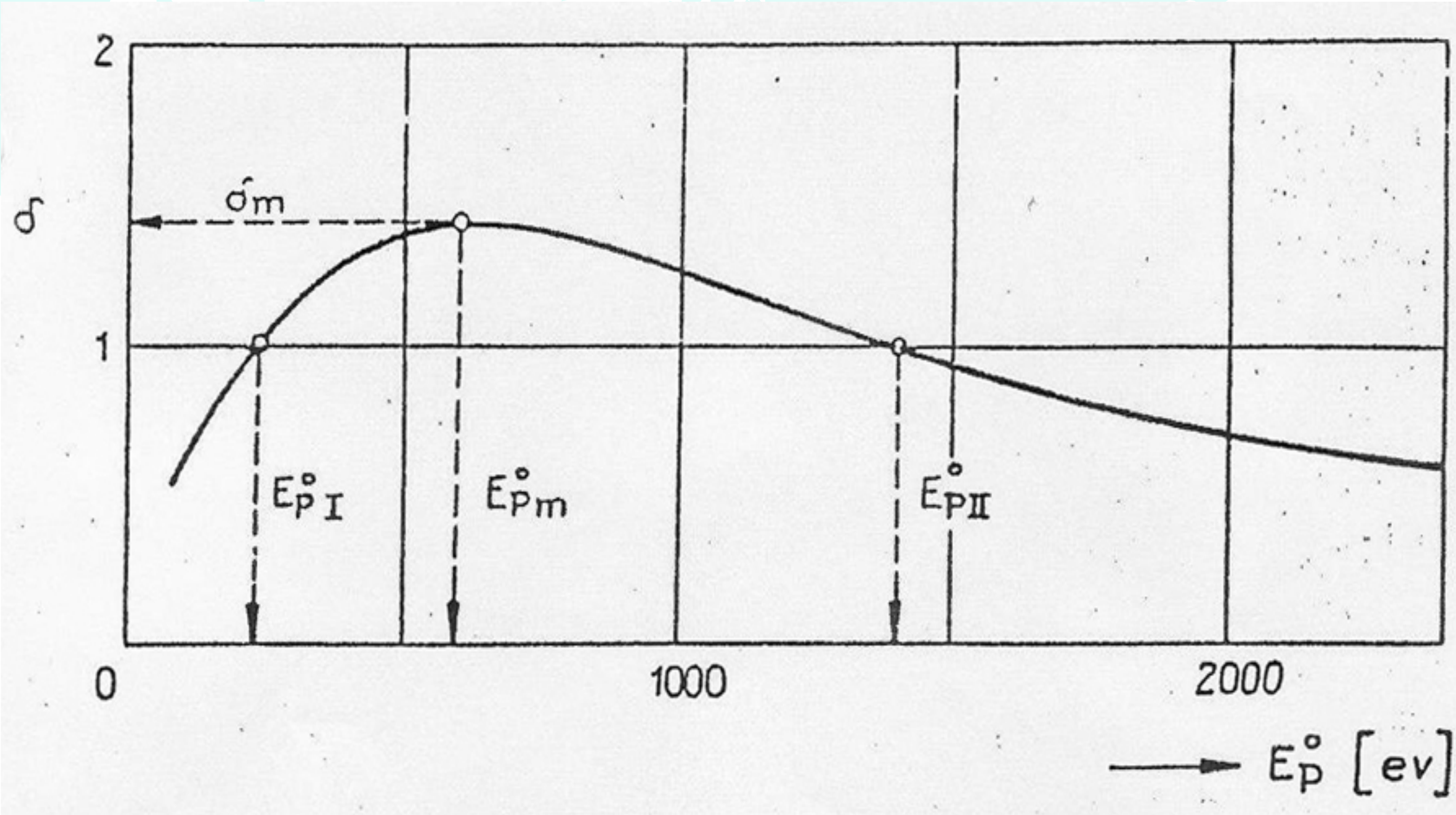
Electron - surface interactions

Secondary electron yield for materials

- Tables and figure on the next slides give the maximum secondary electron yield, δ_{max}, and the primary electron energy, E_p, producing it
- Insulators tend to have extremely high yields since there are no free electrons in the conduction band as opposed to metals; specifically, the conduction band is completely filled with electrons and can accommodate no more; thus the secondary electrons, as they move toward the surface, have not given up energy in small steps, have a better probability of reaching the surface and escaping.

Credit: Ketsdever

Electron - surface interactions



Credit: Ketsdever

Secondary electron yields

Atomic Number	Element	δ_{max}	$E_{p, max}$ (eV)	$E_{p, I}$	$E_{p, II}$
12	Mg	0.95	300	-	-
13	Al	0.95	300	-	-
22	Ti	0.9	280	-	-
26	Fe	1.3	400	120	1400
27	Co	1.2	500	200	-
28	Ni	1.35	550	150	1750
29	Cu	1.3	600	200	1500
37	Rb	0.9	350	-	-
40	Zr	1.1	350	175	600
41	Cb	1.2	375	175	1100
42	Mo	1.25	375	150	1300
46	Pd	>1.3	>250	120	-
47	Ag	1.47	800	150	>2000
48	Cd	1.14	450	300	700
50	Sn	1.35	500	-	-
51	Sb	1.3	600	250	2000
55	Cs	0.72	400	-	-
56	Ba	0.82	400	-	-
74	W	1.35	650	250	1500
78	Pt	1.5	750	350	3000
79	Au	1.45	800	150	>2000
82	Pb	1.1	500	250	1000
83	Bi	1.5	900	80	>2000

Group	Substance	δ_m	$E_{p,m}$ (eV)
Semiconductive	Ge (single crystal)	1.2-1.4	400
	Si (single crystal)	1.1	250
	Se (crystal)	1.35-1.4	400
	C (diamond)	2.8	750
	C (graphite)	1.0	250
	Cu_2O	1.19-1.25	400
	PbS	1.2	500
	Ag_2O	0.98-1.18	-
	ZnS	1.8	350
Intermetallic	GeCs	7.0	700
Insulators	LiF (evaporated layer)	5.6	-
	NaF (layer)	5.7	-
	NaCl (single crystal)	14.0	1200
	NaCl (layer)	6.0-6.8	600
	KCl (single crystal)	12.0	-
	KCl (layer)	7.5	1200
	KBr (single crystal)	12.0-14.7	1800
	BeO	3.4	2000
	MgO (single crystal)	23.0	1200
	MgO (layer)	4.0	400
	BaO (layer)	4.8	400
	Al_2O_3 (layer)	1.5-9.0	350-1300
	SiO_2 (quartz)	2.4	400
	Mica	2.4	300-384

Credit: Ketsdever

Electron - surface interactions

Secondary electron yield for angle of incidence

- Yield of secondaries depends on the angle of incidence of the primary electrons
- More oblique angles produce more secondaries
- The reason is that shallow penetration by primaries (more oblique angle) produces secondaries nearer the surface and secondaries can escape
- Less oblique angle leads to deeper penetration and more opportunity for secondaries to lose energy as the try to emerge to the surface
- Secondaries produced more than ~100 Å (10 nm) deep within a metal stand little chance of escaping

Credit: Ketsdever

Ion - surface interactions

Interaction process - secondary electron yields from heavy ion impact

- These secondary electron yields, γ_i, due to heavy ion impacts range from 0.1 to 0.3 for most metals at moderate (~5 keV) incident energies
- Up to these energies, yields are nearly independent of the kinetic energy of the incident ions for most metals
- Ejection of an electron from a surface occurs through electron excitation into the kinetic energy continuum above the surface potential barrier
- The excitation energy source may be from kinetic energy or internal potential energy leading to kinetic or potential ejection, respectively

Credit: Ketsdever

Ion - surface interactions

Interaction process - sputtering

- Heavy incident ion and surface atom interaction leads to larger sputtering yields than for electron impact
- Heavy incident ions can eject bulk material particles as well as secondary electrons
- Ejected particles can be neutrals or ions (positive or negative)
- Physical sputtering
  - Atoms are ejected from the solid surface as a result of momentum transfer from incident particle (ion or neutral)
  - Kinetic energy is critical
  - This process is the dominant one for ionic species on orbit
- Chemical sputtering
  - Incident particle and surface particle form volatile compound(s) which are subsequently lost due to vaporization
  - Kinetic energy not critical
  - Atomic oxygen (neutral) impacts on surfaces which result in reactions is an example

Credit: Ketsdever

Ion - surface interactions

Interaction process - neutralization

- Ions striking a surface typically leave transformed into a neutral particle
- Ionization energy must be greater than the material's work function (this is usually true except for alkali ions)

Interaction process - X-radiation

- Ions or electrons striking a surface with enough energy can produce continuum X-rays (bremsstrahlung or "braking" emission)
- The production of X-rays is inversely proportional to the square of the mass of the bombarding projectile
- Therefore, electron bombardment produces the greatest X-radiation

Credit: Ketsdever

Current collection

Current balance

- Fundamental physical process in s/c charging is the current balance
- At equilibrium, all currents must sum to zero, $\Sigma I = 0$
- The potential, V, achieved at equilibrium is the difference between the s/c potential and the plasma (floating) potential
- The total current, $I_T(V)$, collected by a s/c at potential, V, is given in (9-2) where I_e is the incident primary electron current on s/c, I_i is the incident ion current, I_{se} is the incident secondary electron current caused by electrons, I_{si} is the incident secondary electron current caused by ions, I_{bse} is the backscattered incident electrons, I_{ph} is the secondary electron current caused by photons, and I_b is the current (both electrons and ions) from active sources such as ion thrusters and experimental apparatus

$$I_T(V) = I_e(V) - I_i(V) + I_{se}(V) + I_{si}(V) + I_{bse}(V) + I_{ph}(V) + I_b(V)$$

(9-2)

Credit: Ketsdever

Current collection

Effect of magnetic fields upon current collection

- For LEO spacecraft, the magnetic field is sufficiently strong that anisotropies which are introduced by the field need to be considered
- Motional electric fields
  - Spacecraft moves across magnetic field lines and sees an electric field from $E = V \times B$
  - The potential difference between the s/c and the plasma varies with location on the surface - and can be up to 26 V on a large structure like space station
- Particle flux anisotropies
  - S/C in magnetic field introduces effect on surfaces such that electrons from $-V \times B$ can be easily trapped but less easily from $V \times B$ and this can be a factor of 2 on some surfaces

Credit: Garrett

BREAK

Spacecraft charging

Basics of spacecraft charging

Spacecraft charging is a variation in the electrostatic potential of a spacecraft (s/c) surface with respect to the surrounding plasma

- Large static charges can interfere with instruments
- Discharge occurs between relatively large potential differences and can lead to problems
  - Spurious electronic switching
  - Breakdown of thermal coatings
  - Amplifier and solar cell degradation
  - Optical sensor degradation
- Insulators and dielectric (non-conducting) materials can differentially charge with respect to other s/c surfaces

Basics of spacecraft charging

Other spacecraft charging factors

- Most reported problems are at high altitudes > 5 R_E (susceptibility to magnetotail particle fluxes)
- Charging is orbit/shape/surface-dependent; for example, a circular orbit, spherical satellite with a homogenous conducting surface would probably not experience significant charging-related problems because the vehicle’s potential would be uniformly high.
- Physical processes couple with s/c design and enable charging
  - Photoelectric effect
  - Plasma bombardment

Credit: Tascione

Coupled processes

Photoelectric effect

- Solar EUV photons illuminate s/c surface during sunlit portion of an orbit
- Photons knock off electrons (photoemission)
- Surface develops a positive charge
- Electrons form a negative plasma cloud (sheath) near the vehicle skin
- Because s/c tend to have non-homogenous surfaces (solar arrays, probes, lenses, shaded areas) there is a marked difference in conductivity across the surface
- This results in differential charging from sunlit to shaded surfaces of the vehicle

Credit: Tascione

Coupled processes

Plasma bombardment

- Charging from plasma bombardment is dependent on the structure
- For a s/c imbedded in a hot plasma, there are constant collisions with charged particles
- Electrons with energies > few keV can penetrate 1 micron or more into the surface; they can remain near or just under the surface (they “stick” to the vehicle skin)
- This causes a negative charge buildup
- Holes or cavities near front (ram direction) of vehicle can “scoop” up particles, i.e., there is a higher flux rate, and there can be increased charging

Credit: Tascione

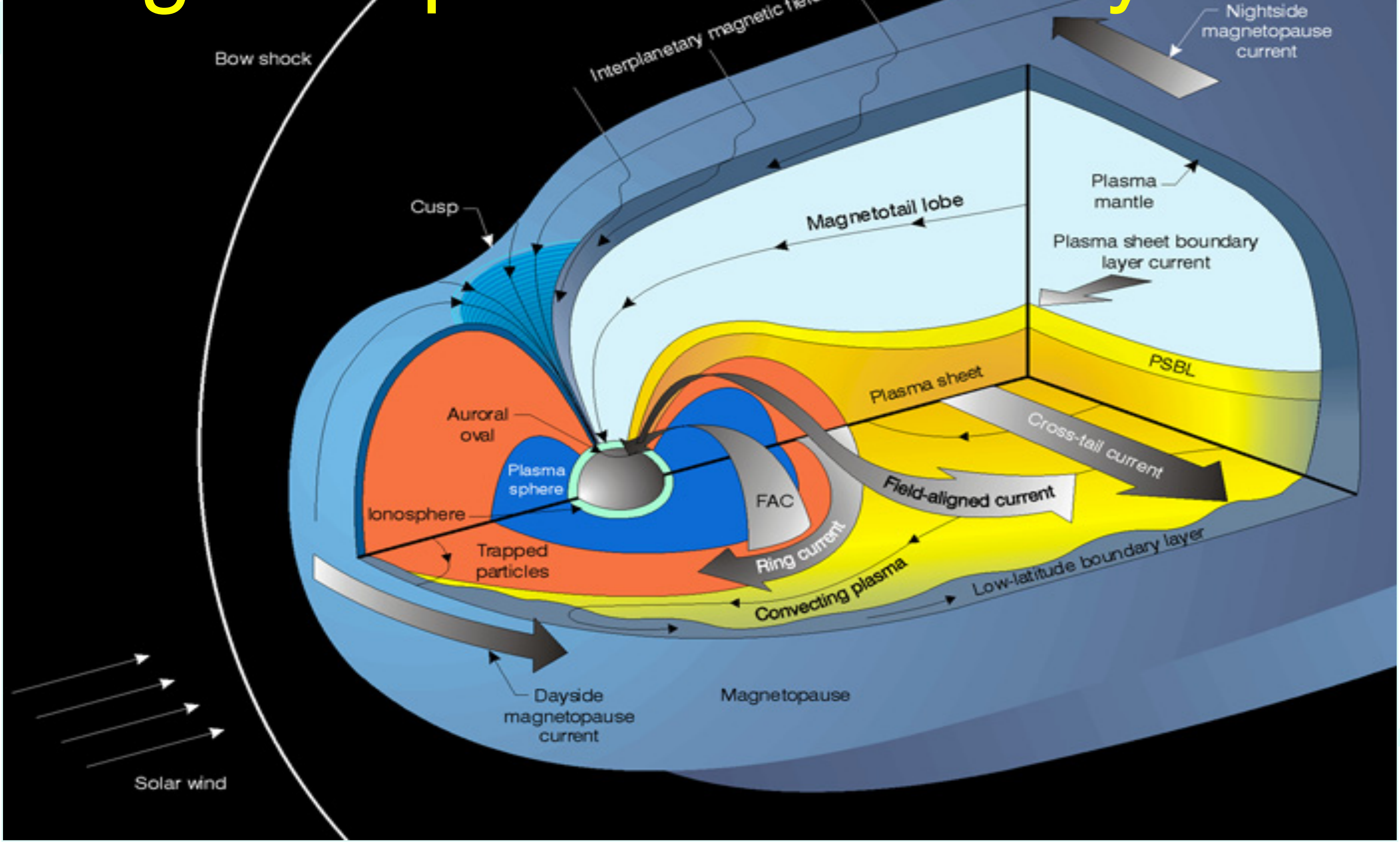
Plasma bombardment

High altitude plasma bombardment

- High altitudes, e.g., geosynchronous orbits, seem to be more susceptible to charging
- Geomagnetic disturbances and substorms result in greater particle injections from magnetotail to inner regions and these events occur several times a day, even on quiet days
- Densities of electrons increase by 3 orders of magnitude and ions by factor of 10
- Particle injections mostly in night sector of magnetosphere and in plasma sheet region that has Earthward plasma motion
- Electrons drift into midnight-dawn sector (eastward)
- Ions drift into midnight-dusk sector (westward)
- Greatest fluxes slightly above and below the geomagnetic equatorial plane (neutral sheet)
- Charging most occurs near local s/c midnight and is nearly invisible to s/c operating on daytime meridians

Credit: Tascione

Magnetospheric Current Systems



Plasma bombardment

Geostationary conditions (35784 km = 5.6 R_E or L-shell of 6.6)

- Charging occurs when s/c are close to magnetopause
- S/C > 5 R_E tend to be immersed in the plasma sheet in the nightside
- Ambient plasma density is low > 5 R_E and the environment cannot easily "bleed off" or neutralize the small charges as they accumulate before a discharge occurs

Basics of discharges

Conditions conducive to discharges

- Discharges can permanently damage s/c materials and electronics
- ANYTIME CHARGING IS OCCURING IS CONDUCIVE TO DISCHARGES
- Sudden changes in the environment may trigger discharge
  - Orbital maneuvers
  - Onset of downlink telemetry
  - Other onboard electronic activity or change in s/c potential
  - Transit of geosynchronous s/c into or out of eclipse (near equinox)
  - Transit of LEO s/c into or out of sunlit
  - High altitude s/c encounter with intense current or magnetosphere boundary

Credit: Tascione

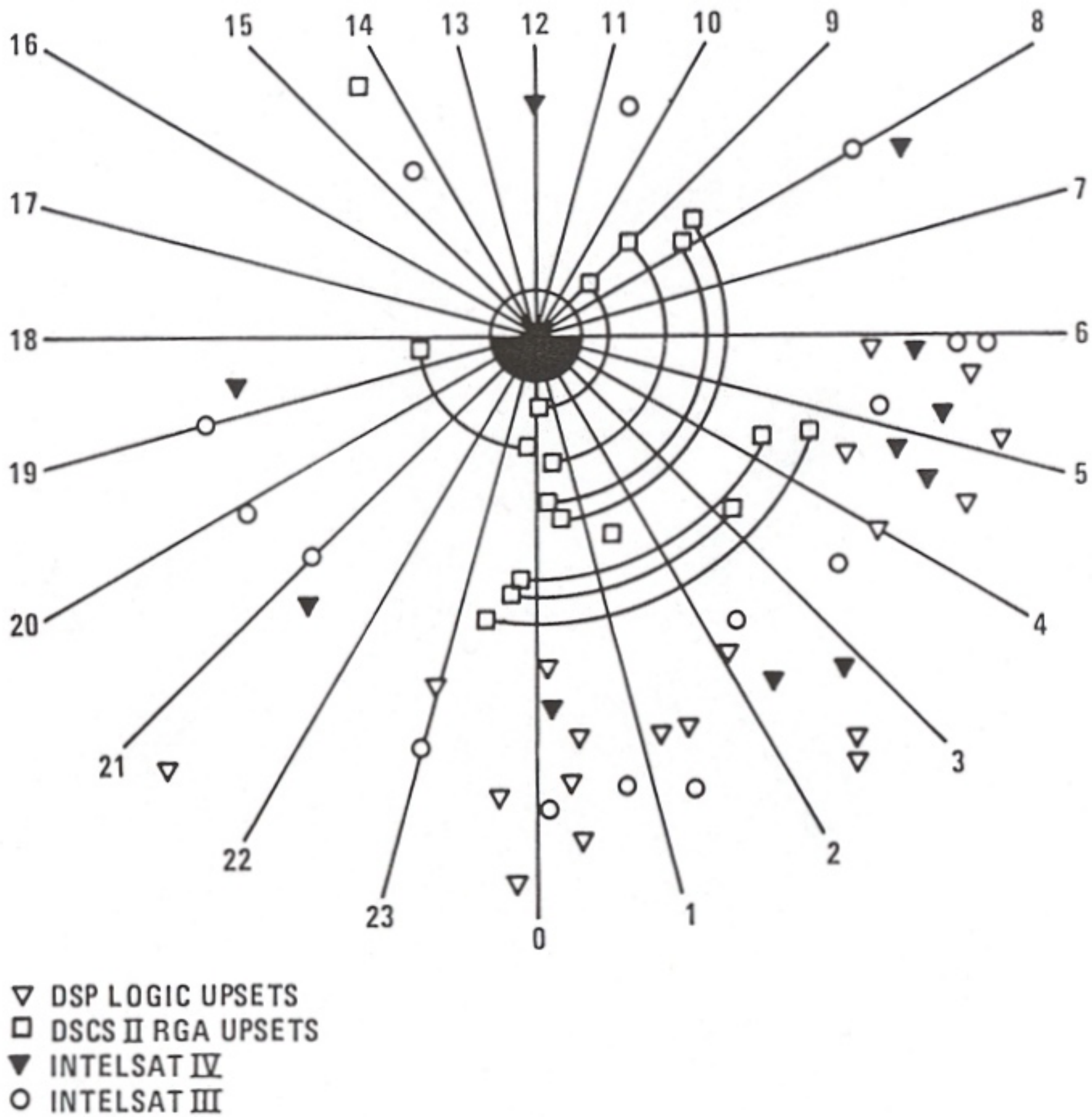
Basics of discharges

Predicting discharges

- Quiet magnetosphere
  - Discharge times statistically occur more often between 0400 and 0600 LT for a s/c in geosynchronous orbits
  - This could be related to eastward electron drift in this sector and substorm/particle injection events
- Perturbed magnetosphere
  - Noon local s/c time is higher probability period for discharges
  - Possibly the s/c encounters the magnetopause boundary in these periods as it is compressed by the solar wind or the dayside magnetopause current affects charging rates
- Least probable discharge period is early evening for a s/c (1900 LT)
- Equinoxes are times of increased discharge probability for geosynchronous s/c

Credit: Tascione

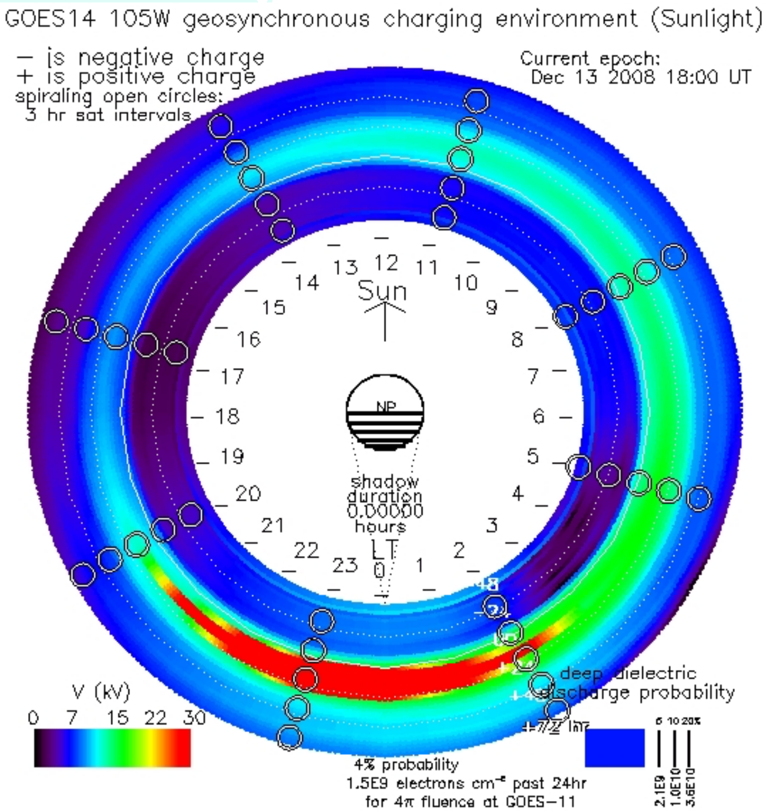
Local Time Plot of Satellite Anomalies in Geosynchronous Orbit

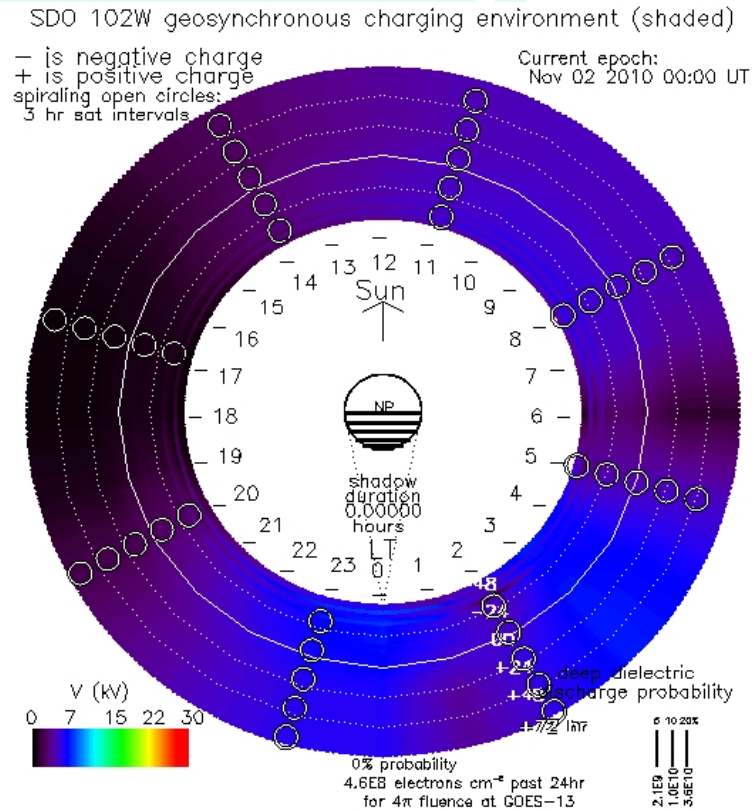


Credit: D.N. Baker

GEO charging (GAPS)

https://sol.spacenvironment.net/gapops/index.html

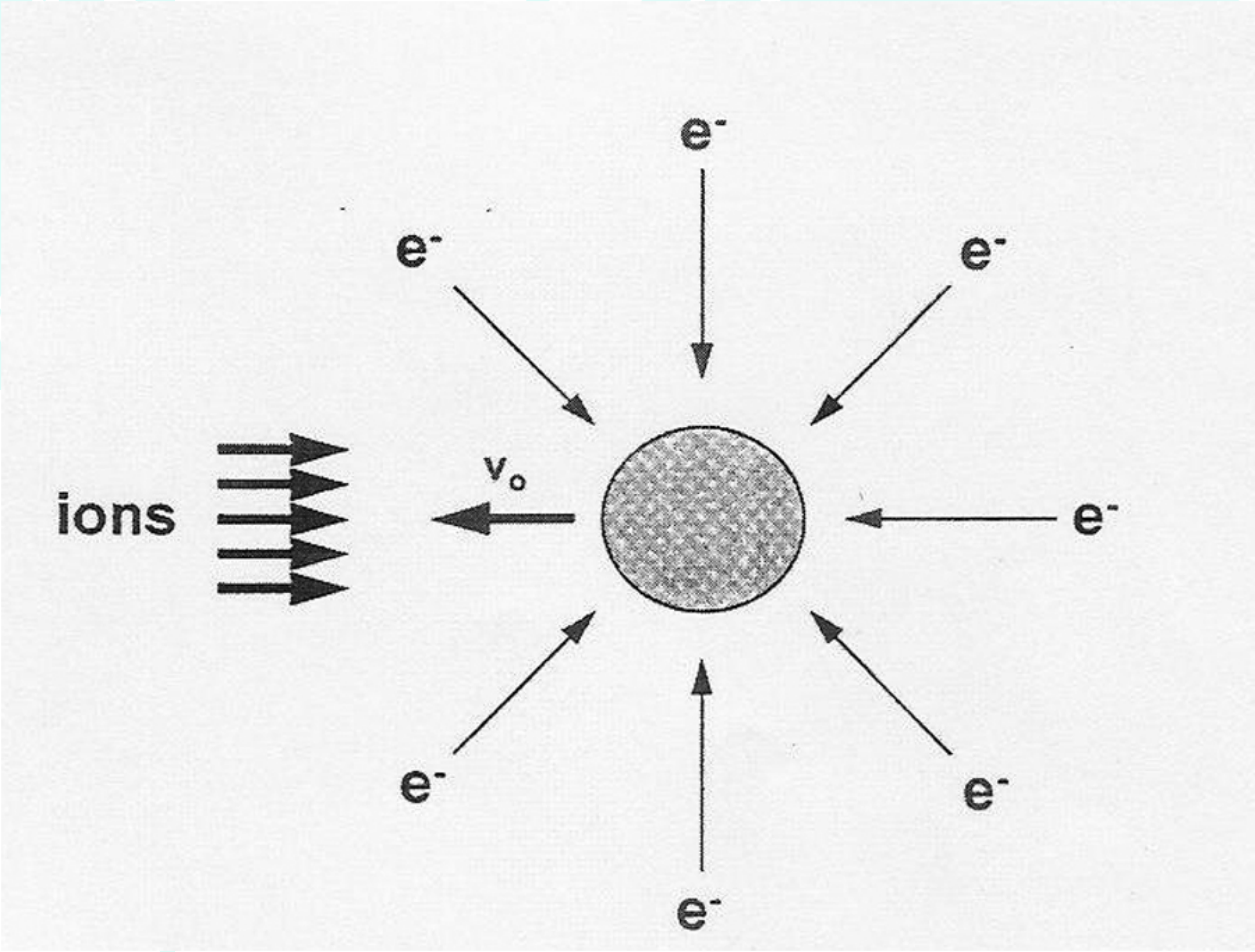




Credit: SET

LEO charging: Unbiased and biased

Unbiased s/c charging



Credit: Ketsdever

Unbiased s/c charging

Difference in electron and ion fluxes results in a floating potential

- Electron thermal speed is >> than s/c orbital velocity
- Ion thermal speed << than s/c orbital velocity
- Therefore, ions impact those surfaces in ram direction
- **Ion current** is

$$I_i = en_0 v_{s/c} A_i \qquad \textbf{(9-3)}$$

where e is the electrostatic *ion* charge (assuming single ionization, also called the *charge intensity*, q, in Coulombs), n_0 is the plasma number density (concentration), $v_{s/c}$ is the s/c orbital velocity (typically ~8 km s^{-1} in LEO), and A_i is the area of the s/c that collects ions

Credit: Ketsdever

Unbiased s/c charging

– **Electron current** is

$$I_e = \frac{1}{4} e n_0 v_{e,th} A_e \exp(\frac{eV}{kT_e}) \qquad \textbf{(9-4)}$$

where $v_{e,th}$ is the average thermal speed of the electrons (typically ~200 km s^{-1} in LEO), $v_{s/c}$ is the spacecraft orbital velocity (Lecture 5 vis-viva integral), A_e is the area of the s/c surface incident area that collects electrons ($4\pi r^2$), V is the s/c potential, k is Boltzmann's constant (1.38×10^{-23} J K^{-1}), and T_e is the electron kinetic temperature (a measure of the electrons kinetic energy; electrons and ions can have approximately same kinetic temperature as the ambient neutrals), charge e = 1.6×10^{-19} C (Coulombs)

– The s/c continues to charge negatively until the s/c potential can repel excess electrons and currents balance.

– At this point, s/c is charged to the **spacecraft floating potential** (units of Volts) given by

$$V_f = \frac{kT_e}{e} \ln(\frac{4 v_{s/c} A_i}{v_{e,th} A_e}) \qquad \textbf{(9-5)}$$

Credit: Ketsdever

Unbiased s/c charging

LEO conditions

- Floating potential ~ -1 V or less
- Floating potential is the potential of the conducting surfaces that are used as the spacecraft's electrical ground as measured with respect to the plasma
- A dielectric or insulator cannot distribute the charge from the surrounding plasma since no conduction bands are available
- Dielectrics may charge to different potentials depending upon their surface conductivity
- In LEO, potential differences can be on order of volts
- In GEO, potential differences can be on order of thousands of volts (leading to arcing)

Credit: Ketsdever

Biased s/c charging

Solar arrays and other s/c surfaces

- S/C surfaces typically have different electrical potentials
- Different potentials will attract different current densities
- Solar arrays are an example
  - Typical potential difference over each cell is about 1 Volt
  - Cells connected in series generate the voltage required by the spacecraft power subsystem
  - Each metallic interconnect in a series is biased at a slightly different potential relative to the s/c ground
  - Therefore, different parts of the solar array will collect current from the plasma in a different manner

Credit: Ketsdever

Biased s/c charging

Solar array current balancing

- If solar arrays face in ram direction at orbital sunrise, all metallic interconnects collect ions
- Potential distribution along the array must arrange itself, relative to plasma, so that ion current collected is equal to electron current
- For the fraction of solar array that is biased less positive than ion impact energy, E_i, ions will "stick"
- Electrons are collected by fraction of array that is biased less negative than electron impact energy, E_e

Credit: Ketsdever

Biased s/c charging

Solar array current density

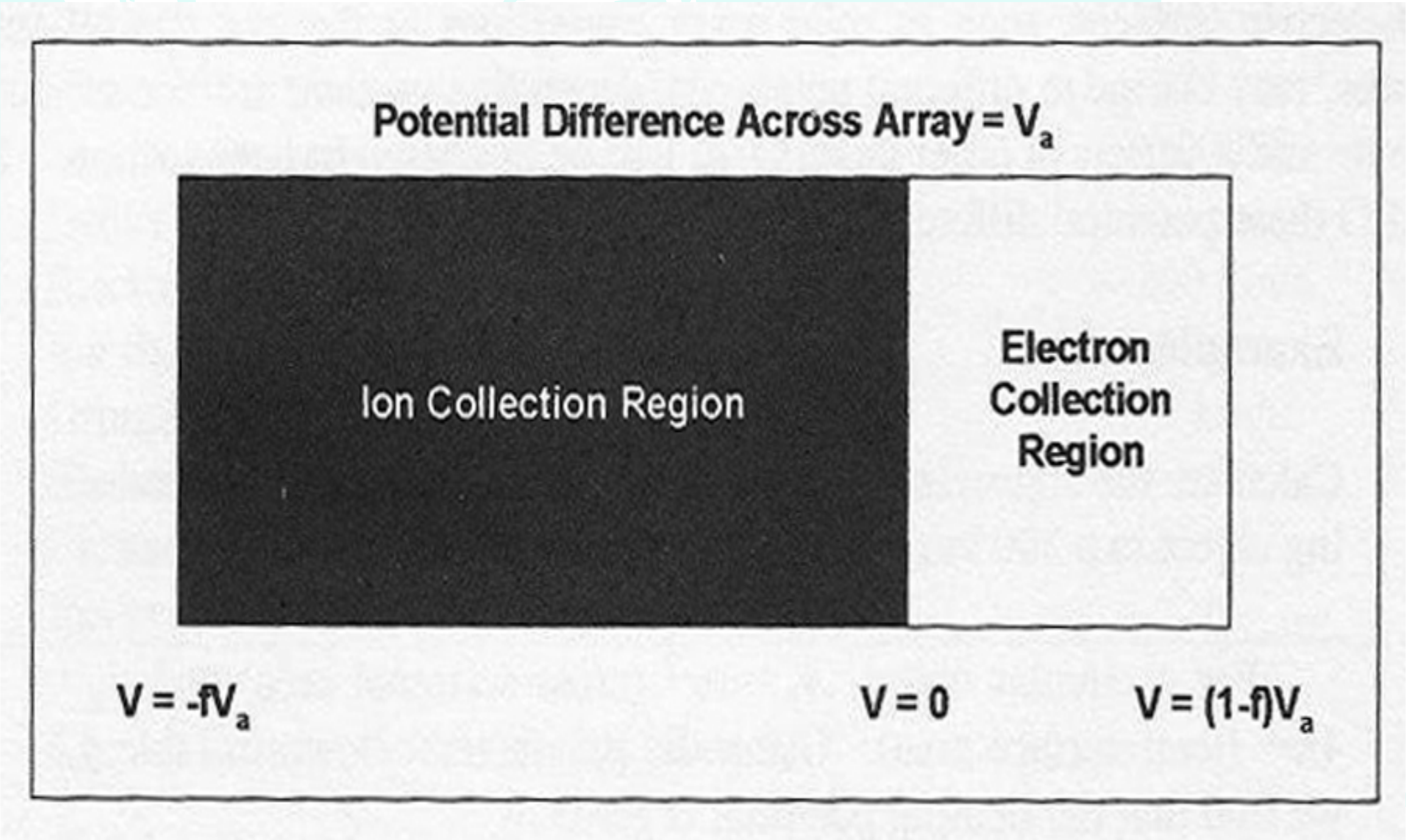
- The solar array current density is a balance between the ion and electron collection
- The majority of the array must float negatively with respect to the plasma to collect a maximum number of slow moving ions; fast moving electrons are collected with ease; current density, j, is given as

$$j_i = e n_0 v_{i,th} \frac{f V_a - E_i}{V_a} \quad \textbf{(9-6)}$$

$$j_e = e n_0 v_{e,th} \frac{(1 - f) V_a - E_e}{V_a} \quad \textbf{(9-7)}$$

with f as the fraction of the array that is biased negatively, and V_a is solar array voltage

Biased s/c charging



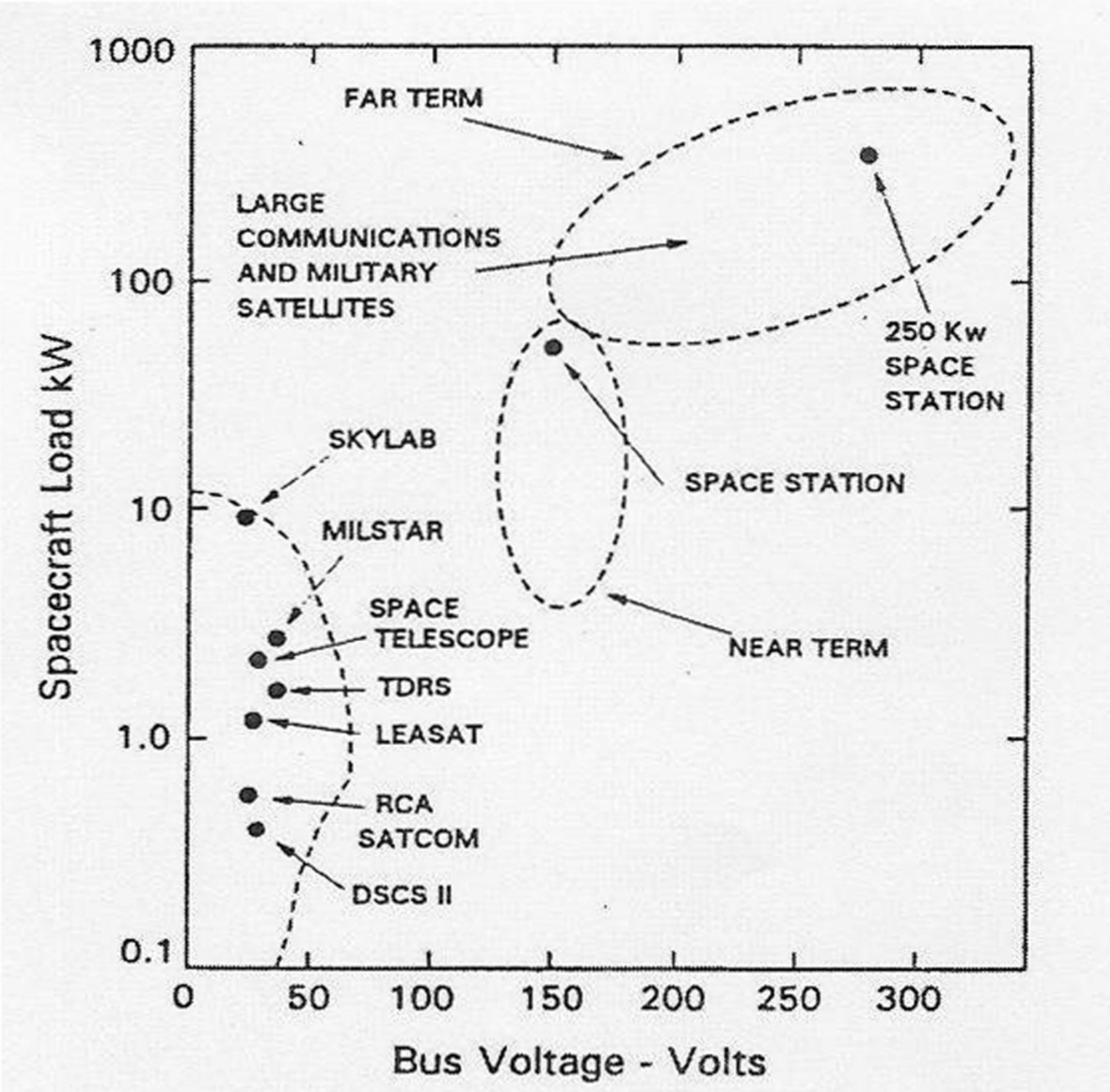
 Credit: Tribble

Biased s/c charging

Solar array ground

- The s/c ground depends on the method used to connect the conducting surfaces
  - the end of the array that floats below the plasma potential is the negative ground
  - the end of the array that floats above the plasma potential is the positive ground
  - no ground at all is a floating ground since both the array and s/c float independent of one another
- Most US spacecraft use -28V ground
- International Space Station (Alpha configuration) was designed for -160V ground

Credit: Ketsdever



S/C grounding voltages trend

Credit: Ketsdever

Grounding

Solar array ground

- For a negative ground, the satellite structure contributes to the collection of *ion* current
  - The array potential will be shifted positive with respect to the plasma
  - A small positive shift in array potential will lead to large increase in electron current collection
  - Even for large s/c structures, s/c will still float a significant fraction of array voltage below the plasma potential
- For positive ground, s/c contributes to *electron* current collection
  - solar arrays would shift negatively and begin collecting ions
  - if solar arrays add small contribution to effective ion collecting area then s/c floating potential is still near plasma potential
- For floating ground, there is no effect on floating s/c potential since satellite and arrays are isolated

Credit: Ketsdever

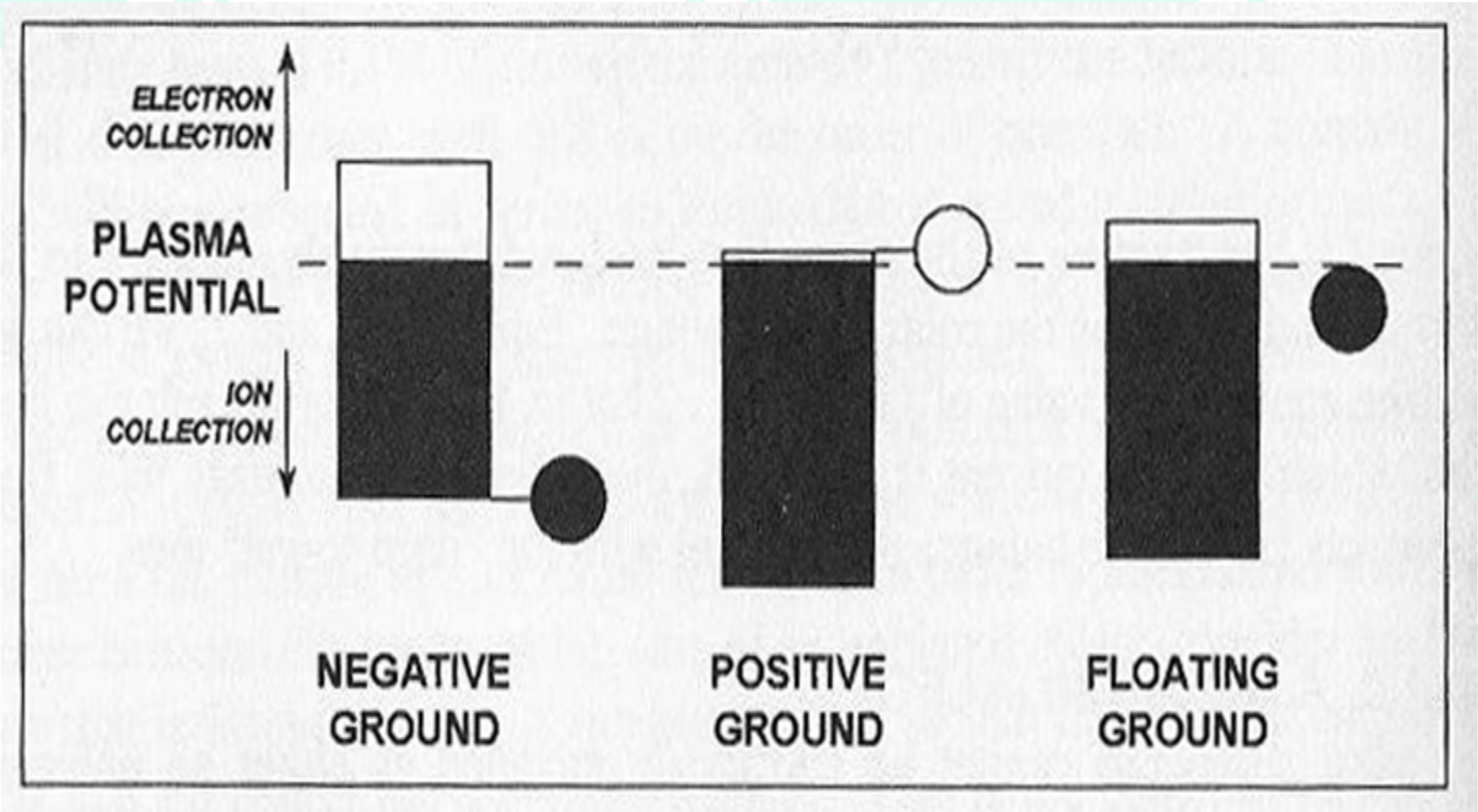
Grounding

Solar array ground

- Negative ground is the usual s/c configuration due to power subsystem constraints requiring current flow to transistors
- Positive ground preferred for scientific payloads where there is as little disruption as possible to ambient plasma
- Floating ground is usually avoided since lack of common ground makes fault detection in an electrical system more difficult; however, floating grounds minimize the possibility of arcing

Credit: Ketsdever

Grounding



W. Kent Tobiska <ktobiska@spacewx.com>
Credit: Tribble

Charging with aurorae

LEO spacecraft passage through high latitude aurora

- Polar-orbiting DMSP F13 satellite experienced a lockup on microwave imaging instrument attributed to electrostatic discharge (ESD) on the vehicle
- The event occurred on May 5, 1995 during a period of intense electron precipitation within a region of very low plasma density in the auroral zone
- S/C frame charged to ~460 V in few seconds
- Subsequent release of potential through ESD led to lockup

Credit: Ketsdever

Field-aligned currents

Field-aligned currents are found in high latitudes

- For LEO spacecraft, current collection parallel to magnetic field line is different than collection perpendicular to field line
- Since electron gyro-radius is ~ 5 cm (smaller than s/c surface) then most electrons are collected parallel to **B**
- Ions have gyro-radius of ~ 5 m, larger than most s/c surfaces, so most ion collection is perpendicular to **B**

High altitude charging: GEO and SCATHA

GEO spacecraft potentials

GEO spacecraft surfaces

- Usually consist of a mosaic of elements from many different materials
- Multiple components of thermal blankets, insulators, coverglasses, aluminized layers, paints
- Designs usually call for all conductive surfaces to be grounded to s/c bus
- Debye length at GEO is usually larger than typical s/c sizes
- Therefore, a highly biased part of s/c may affect current collection in another part of s/c

Credit: Garrett

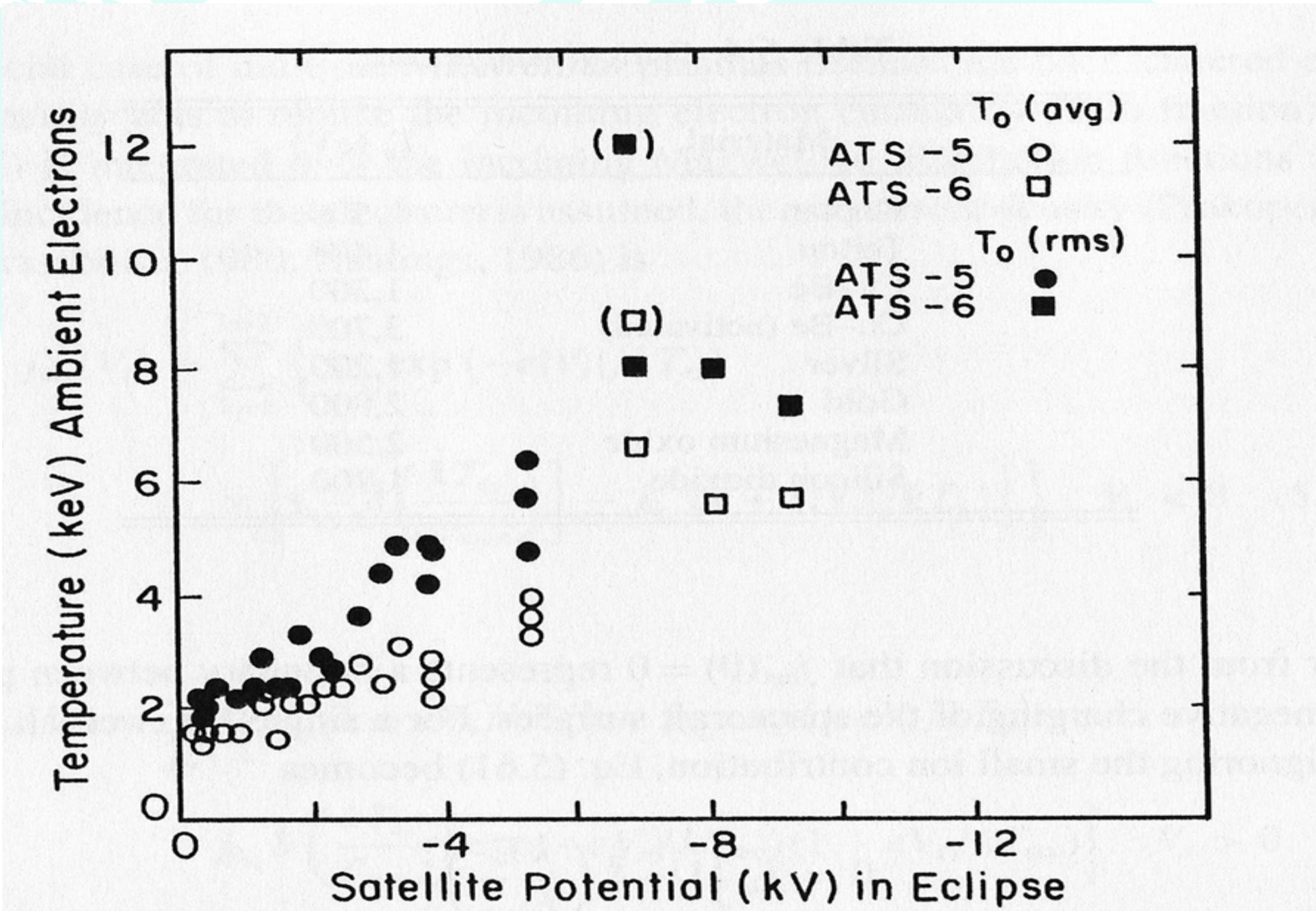
GEO spacecraft potentials

S/C potential has a (kinetic) temperature dependence (expressed in keV)

- For low electron energies (< 1500 eV) there tends to be positive charging of GEO s/c surfaces. This is due to photoemission processes where solar EUV photons remove surface layer electrons leaving a net positive charge
- For higher electron energies (>1500 eV which is the critical electron temperature/energy), there is an abrupt and large surface potential change and negative charging begins

Credit: Garrett

Critical temperature charging



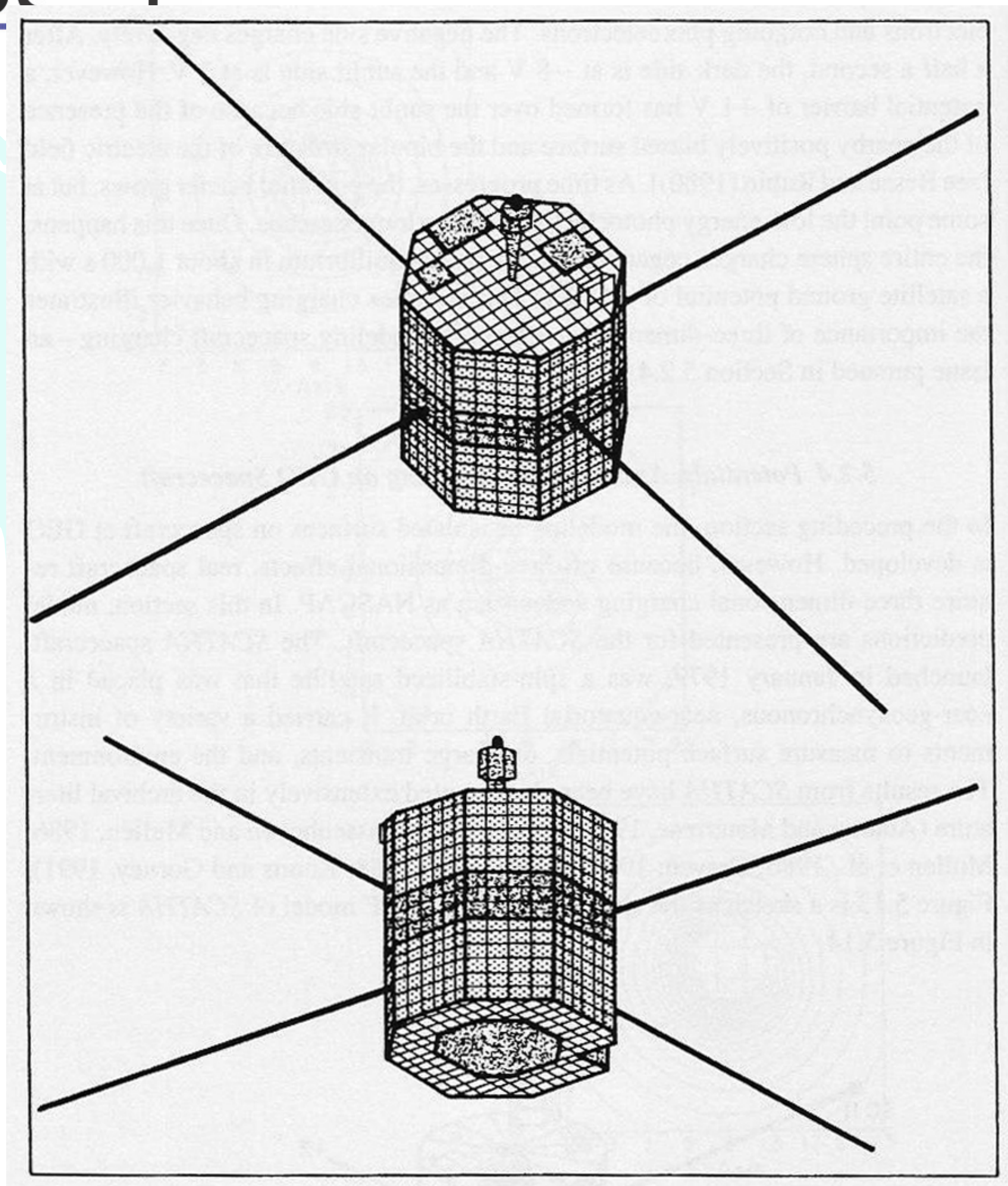
Credit: Garrett

SCATHA example

SCATHA (Spacecraft Charging AT High Altitude)

- Near geosynchronous (5.3-7.8 R_E), equatorial orbit
- During solar cycle 21 maximum (1979-1980)
- Measured surface potentials, discharge transients, and the environment
- Differential charging occurred often; for example, during severe substorms, after 20 minutes, solar cell coverglasses reached -15,600 V while s/c bus was -15,200 V
- Average potential was 2-3 keV (much higher than LEO)
- S/C geometry allowed differential charging with 6 distinct underlying conductors and a solar-cell covered surface

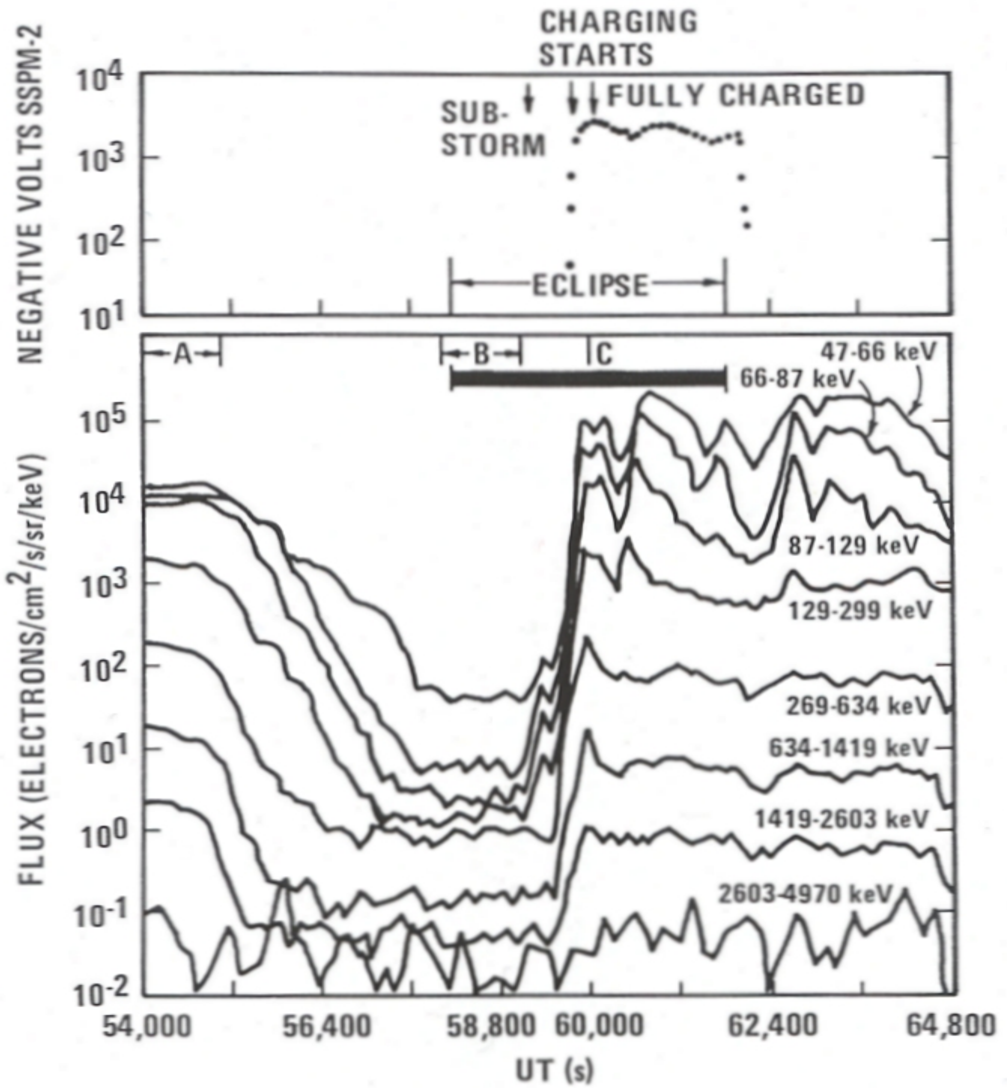
Credit: Garrett



Surface Charging: SCATHA Spacecraft

Credit: Garrett

Surface Charging: SCATHA Spacecraft



UT	15.00	15.67	16.33	16.67	17.33	18.00
LT	21.90	22.74	23.52	23.89	0.59	1.25
L	6.63	6.90	7.14	7.26	7.51	7.76

SCATHA (*Reagan et al.*, 1981)

Credit: D.N. Baker

SCATHA lessons

Design guidelines from SCATHA for GEO satellites

- All conducting elements, surface and interior, should be tied to a common electrical ground, either directly or through a charge "bleedoff" (neutralizing) resistor
- For differential charging control, all s/c exterior surfaces should be at least partially conductive
- The primary s/c structure, electronic component enclosures, and electrical cable shields should provide a physically and electrically continuous shielded surface around all electronics and wiring
- Electrical filtering should be used to protect circuits from discharge-induced upsets

Results of charging - electrostatic discharge (ESD): Paschen discharge and arcing

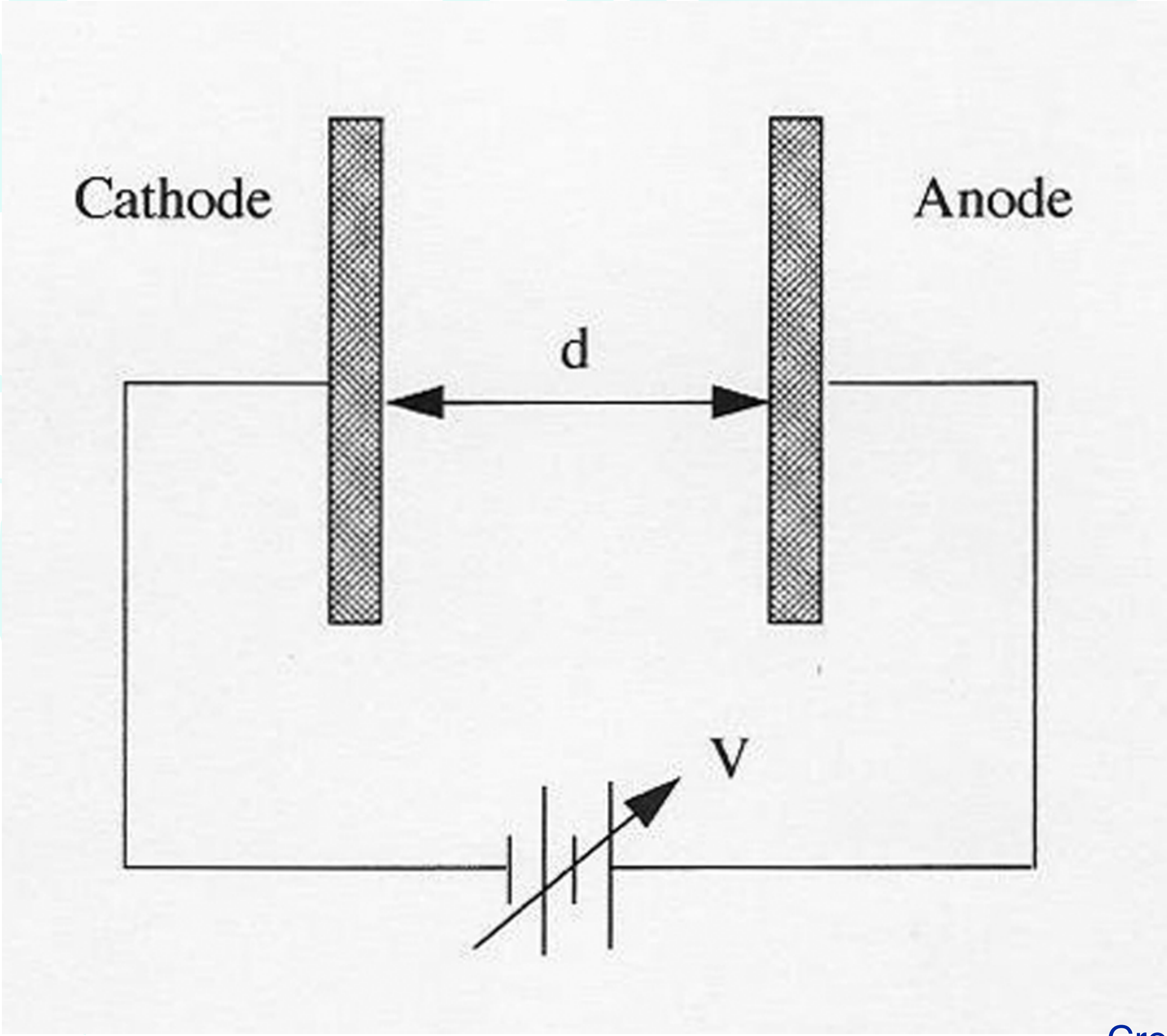
Electrostatic discharge

ESD initiates when the potential between two parts of a s/c increases and a sparking potential, Vs, is reached

- Discharge occurs over large distances at low pressures
- Direction, strength (amount of current flow), and number (several versus one discharge) are unpredictable
- Sparking potential, Vs, is the minimum voltage required under the conditions of a potential gradient
- The anode only needs to be more positive (or less negative) than the cathode
- Sparking potential is a function of the gas (plasma) pressure, p, in the gap and the gap distance, d

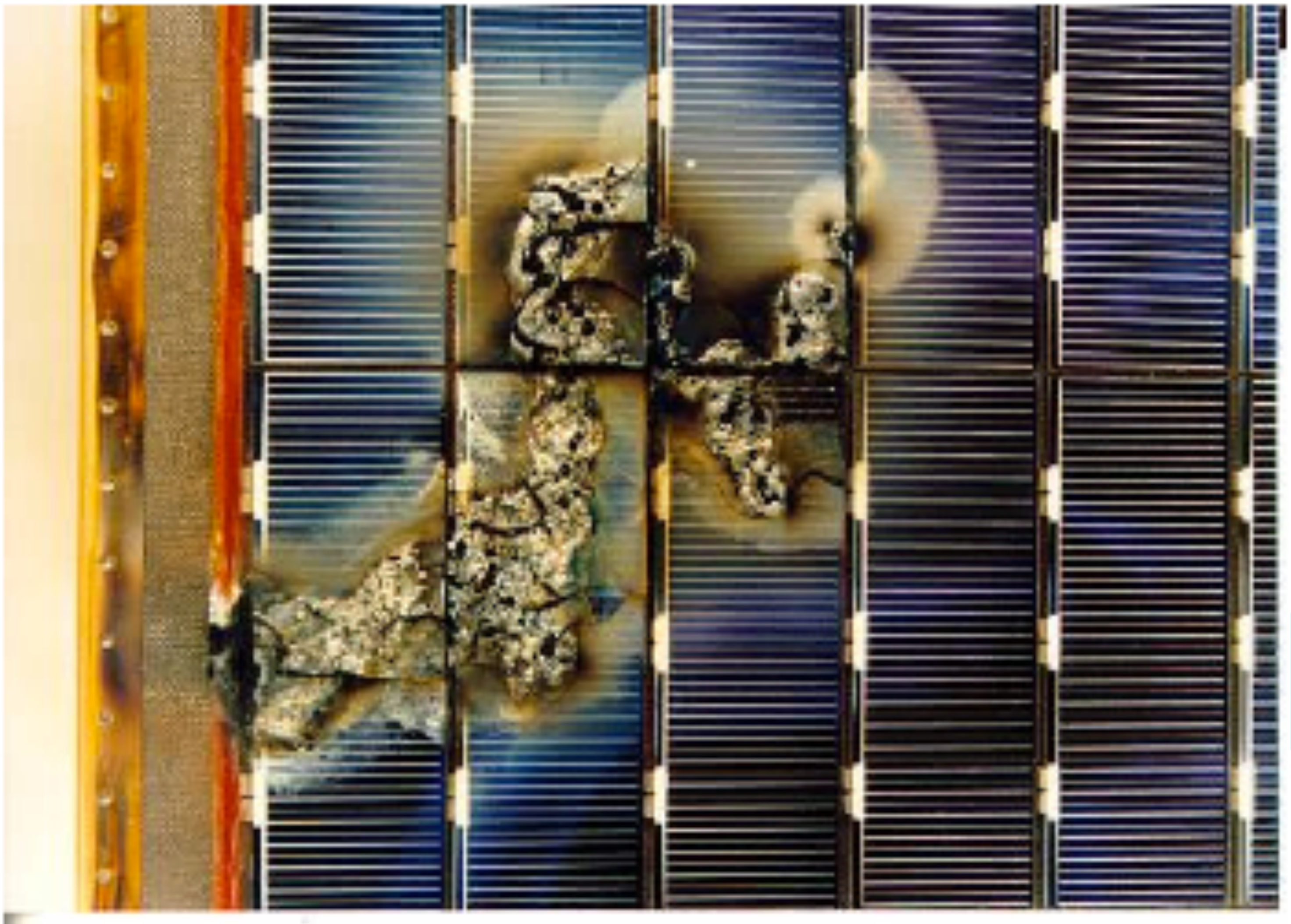
Credit: Ketsdever

Sparking potential



Credit: Ketsdever

Electrostatic discharge



Credit: Ferguson

Paschen discharge

Paschen's Law

— Describes the sparking potential, Vs, for a gas between two electrodes for A, B, and γ as constants that are experimentally determined for a gas (plasma); γ is the yield of secondary electrons from a given surface per incident positive ion; p is the gas pressure and d is the gap distance

$$V_s = \frac{Bpd}{\ln[\frac{Apd}{\ln(1/\gamma)}]} \qquad (9\text{-}8)$$

— Therefore, for a given material, the sparking potential is only dependent upon the quantity p × d

Credit: Ketsdever

Arcing

ESD on a short time scale is arcing or sparking

- Usually there is a large current flow, not self-sustaining, and is defined on solar cells as a sudden current pulse of up to 1 Amp lasting a few microseconds or less
- Can occur by energetic particle charge deposition in dielectric materials during spacecraft charging
  - Electrons between 10-100 keV lose energy at a rate of $R = 1\times10^6 - 5\times10^7$ eV cm^2 g^{-1} depending upon the electron energy and the material

Credit: Ketsdever

Arcing

- The incident electrons penetrate to a few microns where they form a space charge layer
- Charge builds up until a critical value is reached (Paschen's Law) wherein breakdown or arcing occurs
- Breakdown is accompanied by material vaporization and ionization
- Discharges typically initiate at sharp edges such as holes, cracks, seams, or edges of a material
- Water dumps, thruster firings, and outgassing can temporarily increase gas pressure near a surface and thus reduce the minimum potential required for sparking (Vs)

Credit: Ketsdever

Design considerations: Materials selection and plasma contactors

Materials selection

Mitigate differential charging and discharge

- Design considerations include common grounds for all structural and mechanical parts in a s/c
- All exterior surfaces should be at least partially conductive to reduce charging by tying them to a common ground (add thin metallic coatings to insulating material)
- Minimize outgassing properties of materials
- Minimize low secondary electron emissions from materials

Credit: Ketsdever

Plasma contactors

Plasma contactors prevent charge accumulation by providing a low impedance electrical connection between s/c surface and the space environment

- Preventative measure for both gross s/c charging and differential charging of specific s/c surfaces
- Establishes a firm reference potential (the local plasma potential)
- Emits a cloud of charged particles

Credit: Ketsdever

Plasma contactors

Plasma contactors are used to create an artificial plasma environment

- It is a discharge source such as hollow cathode or ion thruster using xenon gas
- Gas is partially ionized by electron bombardment
- The dense, low temperature plasma that is created expands into surrounding s/c space
- Example of a negatively biased s/c
  - It preferentially attracts ambient ions
  - Plasma contactor will supply electrons to balance the positive current collection
  - Enables active control of spacecraft potential

Credit: Ketsdever

Resources

- Design Guidelines for Assessing and Controlling Spacecraft Charging Effects, NASA Tech. Paper 2361, Sep 1984.
- *Spacecraft-Environment Interactions,* Hastings and Garrett, Cambridge Univ. Press, 1996.
- *Introduction to the Space Environment,* Tascione, Krieger Pub. Co., 1994.
- Low Earth Orbit Spacecraft Charging Design Standard Requirement and Associated Handbook, AIAA S-115-2013

Summary

- **Environmental effects (plasma)**
  - Plasma effects
    - Electron and ion surface interactions, current collection
  - Spacecraft charging
    - Sources of charging
      - Photoelectric effect, plasma bombardment, discharge
    - LEO charging
      - Unbiased, biased (solar arrays), grounding, within auroras, field aligned currents
    - High altitude charging
      - GEO, SCATHA
  - Results of charging - electrostatic discharge (ESD)
    - Paschen discharge and arcing
  - Design considerations
    - Materials selection and plasma contactors
  - Resources