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APPLIED PHYSICS LABORATORY

Space Weather and Climatology in Earth's Inner Magnetosphere

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Thanks also for input from: Christine Gabrielse (Aerospace), Justin Likar (APL), and Paul O'Brien (Aerospace)

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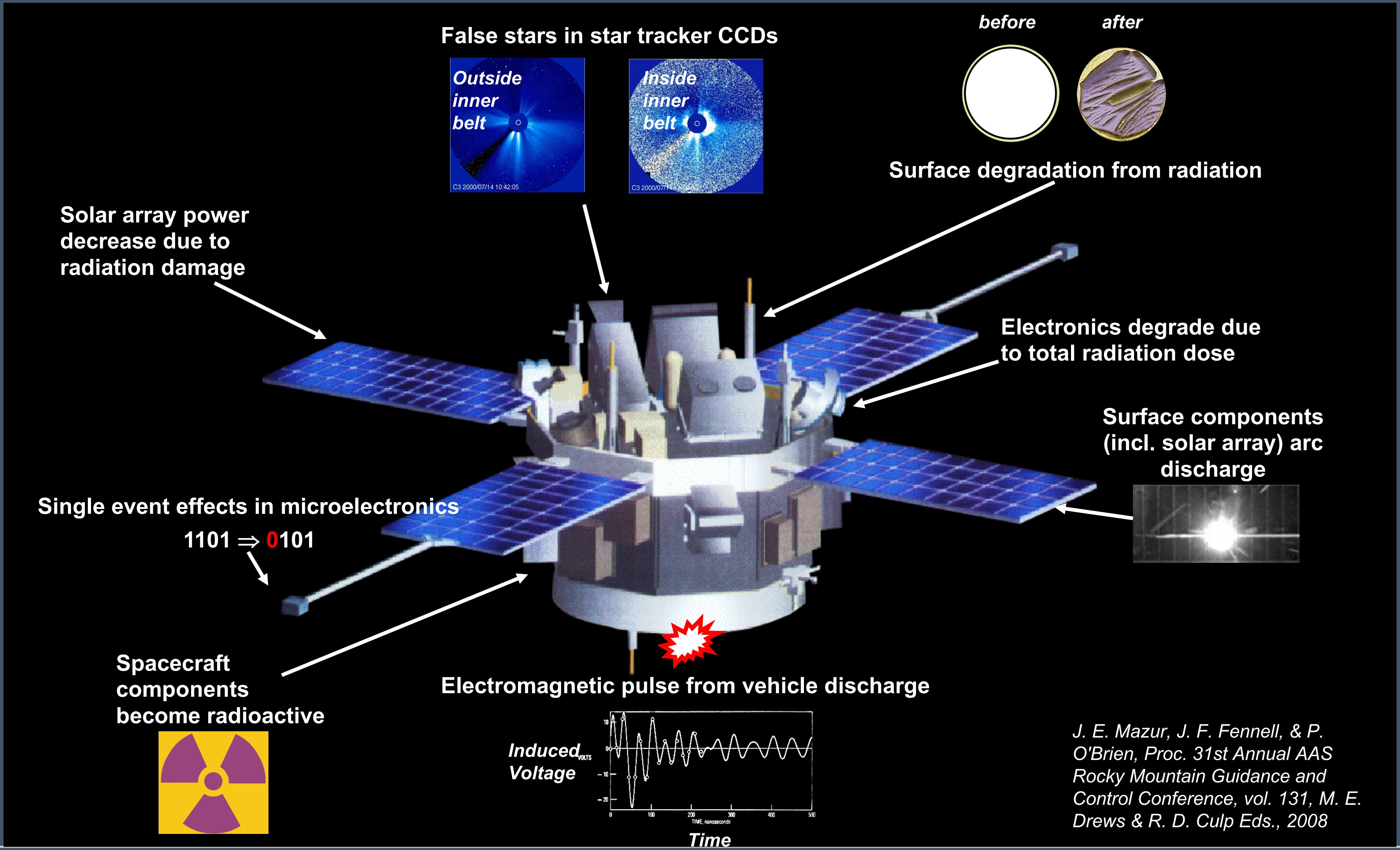
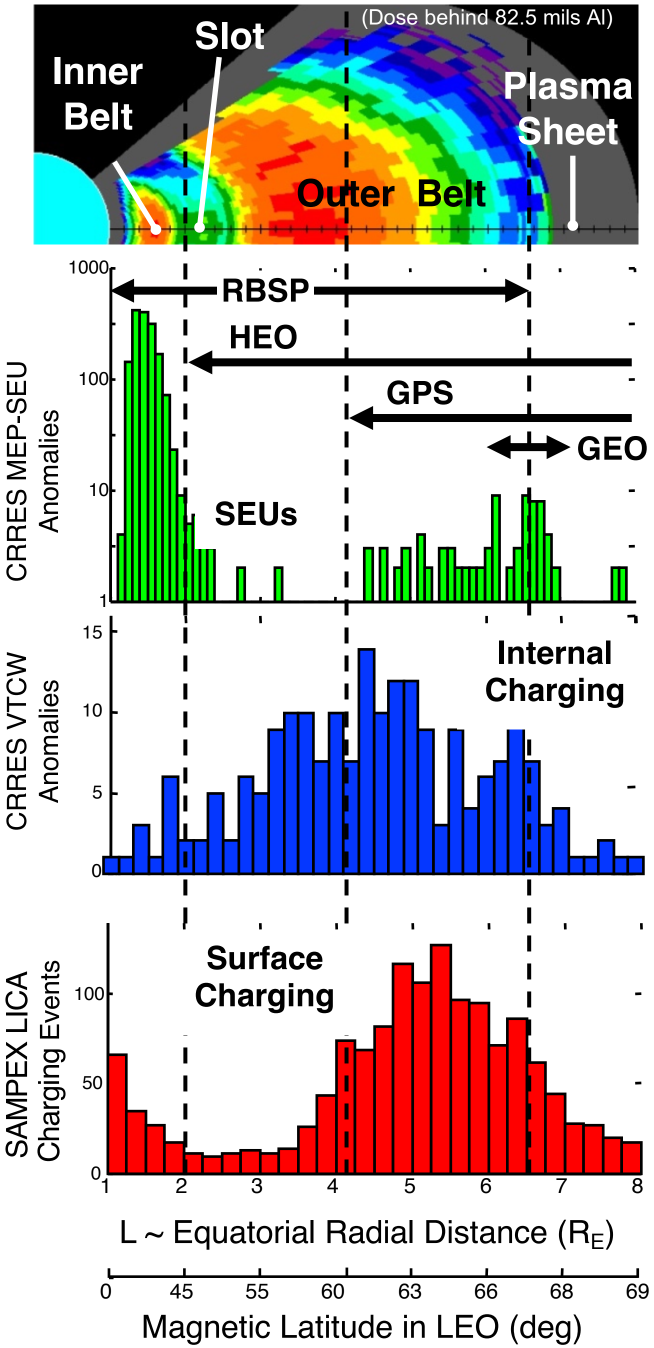
Space Environment Hazards





Hazard Climatology in the Inner Magnetosphere

- Total Ionizing Dose (TID) and Total Non-Ionizing Dose (TNID)
  - Caused by ~MeV electrons and multi-MeV protons
  - Driven by flux intensity
  - Requires hours to years of accumulation
- Single Event Effects
  - Caused by multi-MeV protons and heavy ions
  - Driven by flux intensity
  - Essentially instantaneous (~speed of light)
- Internal Charging
  - Caused by >0.1 MeV electrons
  - Driven mainly by flux, affected by spectrum and materials
  - Typically requires hours to months of accumulation (large variation)
- Surface Charging
  - Caused by keV electrons
  - Usually diagnosed with L, MLT or local temperature/spectrum
  - Heavily influenced by material properties, which change on orbit!
  - Shadow, timing and location are hugely critical; can be very sudden (near-instantaneous to seconds)

Content courtesy of Paul O'Brien

Space Weather *and Climatology*

- Space Weather consists of:
  - Event onsets and sudden *temporal* (not just spatial boundary crossings) changes in radiation intensity
  - Characteristic times < 1-min (energetic particle injections) to a few days (radiation belt enhancements during geomagnetic storms)
  - Largely used in anomaly triage, anomaly resolution, and some operations
  - Space weather observatory data can be used for forensics efforts and data-assimilative nowcast and forecast models
  - Sometimes considered during design and verification

- Space Climatology consists of:
  - Statistics (e.g., mean, 95% confidence interval, extreme worst-case) of hazardous environment conditions (e.g., radiation belt intensities, energetic electron injections, SEPs) observed *as a function of location*
  - Ideally, statistical data cover all varieties of orbits relevant to each particular hazard: LEO, MEO, HEO, highly elliptical, GEO, Lunar transfer, Lunar, L1-halo, etc.
  - Characteristic times > 1-year but includes/captures periodic trends on faster time-scales
  - Largely used in requirements definition and verification
  - Climatological data sets can also be used for anomaly forensics efforts and studies
  - Sometimes considered for risk/hazard threshold analysis

- **Both Space Weather *and Climatology* are critical aspects for spaceflight operations!**

(space climatology) + (space weather) = (risk mitigation)

What Scientists Offer vs. What Operators Need

- The goal of physicists is most often to be able to predict the behavior of a system
- The space research community (scientists) often overestimate the value of space weather forecasts to satellite operators

The Priority Mismatch Between Space Science and Satellite Operations

T. P. O'Brien, J. E. Mazur, and J. F. Fennell

Citation: O'Brien, T. P., J. E. Mazur, and J. F. Fennell (2013), The Priority Mismatch Between Space Science and Satellite Operations, *Space Weather*, *11*, doi:10.1002/swe.20028.

- Satellite operators require tools and data for the following:
  - Forecasts/nowcasts (*space situational awareness*)
  - Anomaly triage (*critical asset perspective: was the anomaly from the environment or a malicious attack?*)
  - Root cause analysis and anomaly resolution (*forensics engineering for mitigation of risk on future efforts*)
- Very few operations in space require a good forecast of the space environment and even fewer (exceptions include extravehicular activity and special tests) will modify their operations in anticipation of a space environment hazard
- Nowcast capability is valuable for anomaly triage and attribution with small lag-times
- The highest priority for operators is triage: the ability to assess the space environment as a factor in anomaly resolution during the first 24-hours after an anomaly occurs
- ***Real-time monitoring combined with good climatological models and datasets are critical!***

Hazards in the Inner Magnetosphere

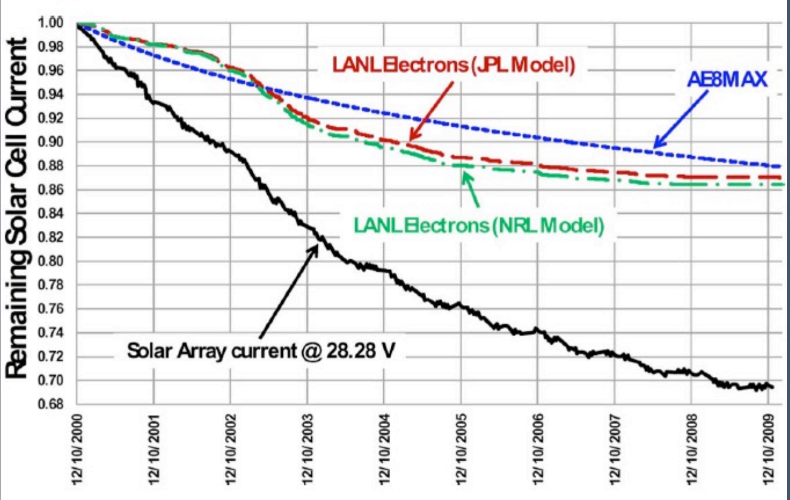
(…and now onto what you asked me to talk about here)

Total Ionizing Dose (TID) and Total Non-Ionizing Dose (TNID)

- Climatological models needed to assess this risk provided orbit of a designed mission
- Spacecraft shielding can be modified (engineering analysis and design) to allow for longer mission life provided knowledge of TID effects on all satellite components
- What we have now:
  - AE9 (electron radiation belts) + AP9 (proton radiation belt) + ESP / PSYCHIC (solar energetic particles)
  - Decades of historic plus ongoing observations to feed climatological model development
  - Example from a new forensics tool from Christine Gabrielse @ Aerospace (next slide)
- ***Gap analysis* - What we need going forward:**
  - **Ongoing observations to feed climatological model development (more stats = more accurate models; think machine learning and data analytics) and for forensics efforts (e.g., solar cell degradation, next slide)**

TNID and Solar Cell Degradation

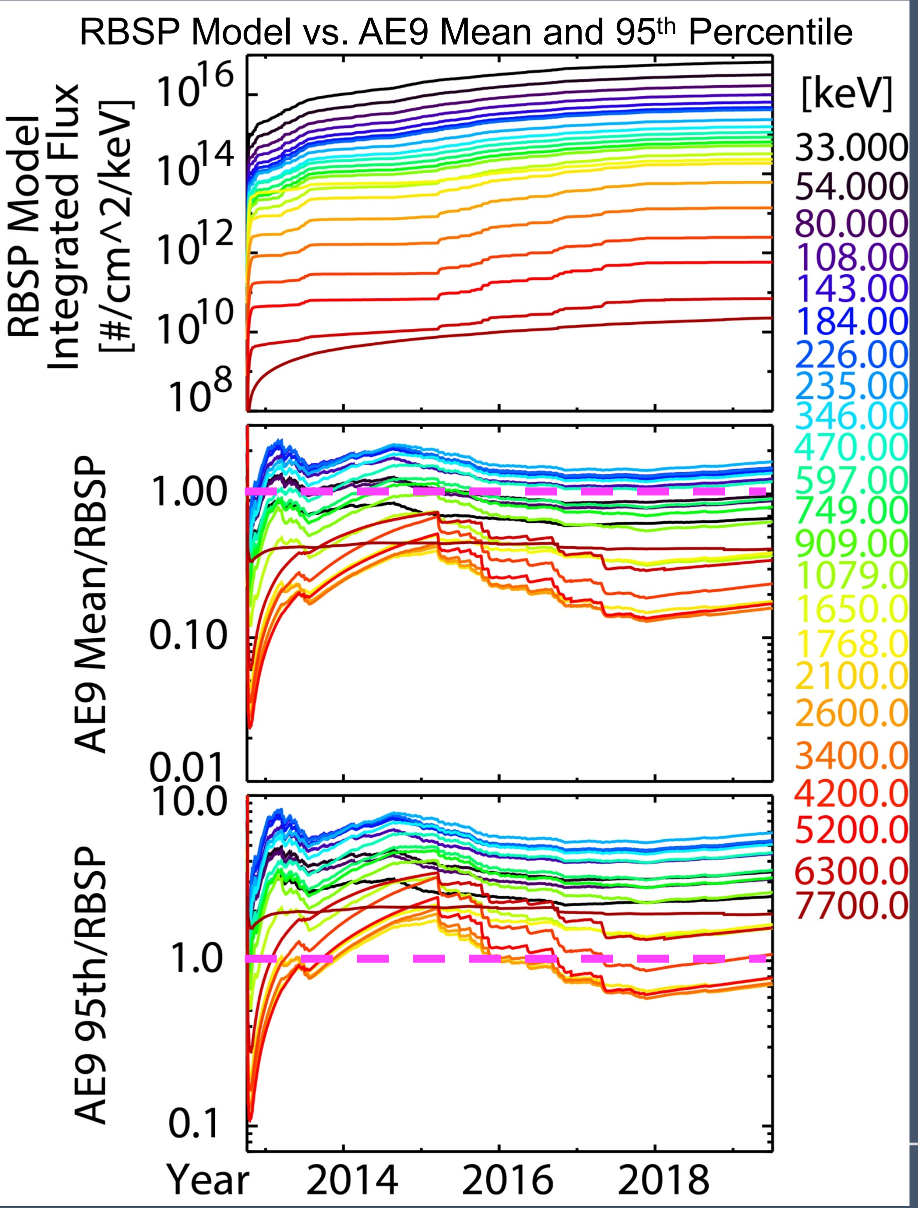
- Solar cell performance on GPS has degraded much faster than modeled expectations (see below) resulting in end of life sooner than designed ($$$)
- Christine Gabrielse at Aerospace Corp. has led a team to develop a new tool allowing spacecraft to be “flown through” the actual radiation environment measured by Van Allen Probes
- Results (figure to right) show that AE9 (current state-of-the-art climatological model for electron radiation belts), does not capture accurate time-variation in the system (e.g., storm-time jumps in fluence) and the RBSP model provides most accurate “to-reality” representation of the environment encountered by the GPS s/c



Messenger et al., 2011
IEEE TRANSACTIONS ON NUCLEAR SCIENCE

- Note, the climatological model worked as designed: it predicts the range of observed fluence to inform the satellite design; however, it is not functional for diagnostics (forensics) as it does not capture the actual variations specific to particular time periods
- This highlights the need for real-time, continuous monitoring of the environments that contribute to TID effects: SEPs, radiation belts, >100 keV ring current protons

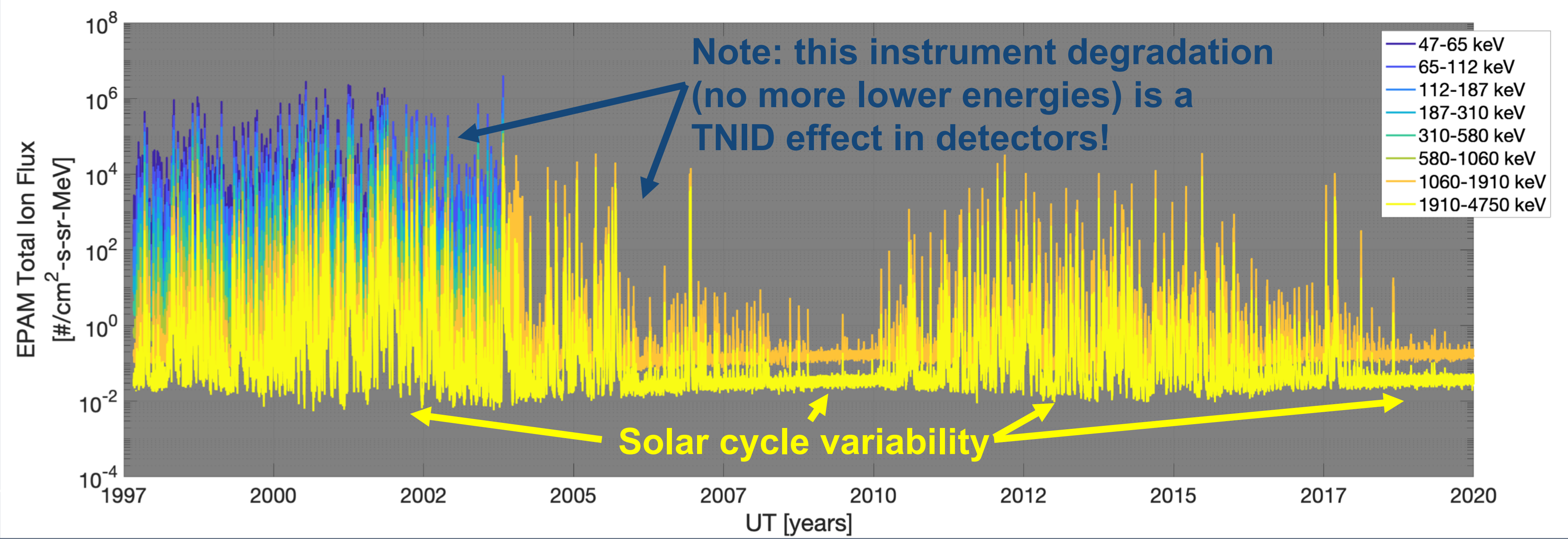
- Plot fluences (time integrated fluxes)
  - *Fluences are inputs to solar cell degradation models*
- Ratio < 1 means AE9 underestimates actual fluence from the RBSP model



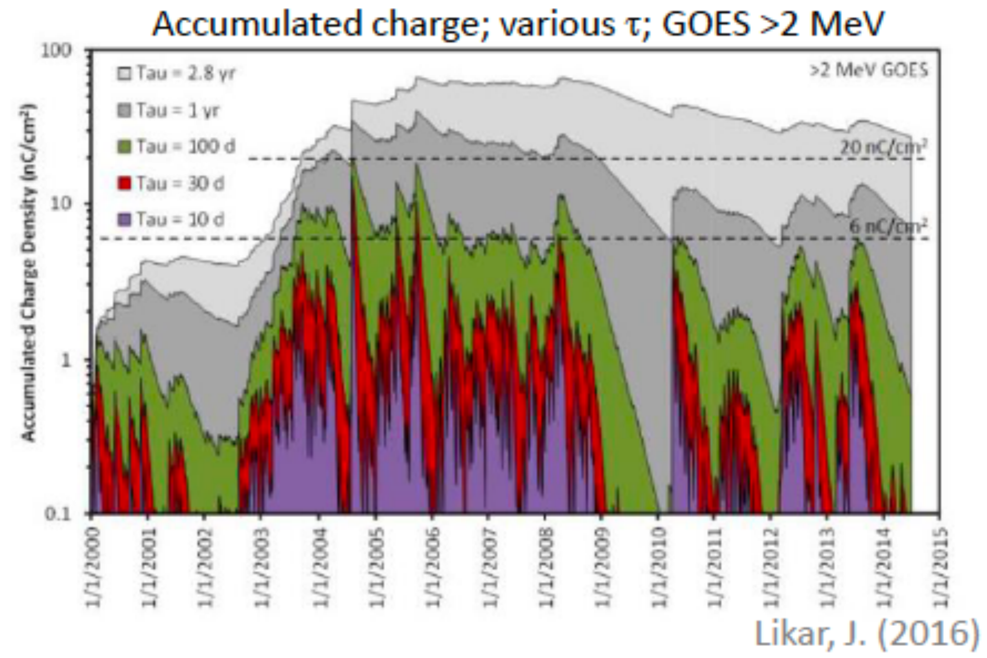
Single Event Effects (SEE)

NON-DESTRUCTIVE SEE	*DESTRUCTIVE SEE*
Single Event Upset (SEU)	Single Event Latchup (SEL)
Single Event Transient (SET)	Single Event Gate Rupture (SEGR)
Single Event Functional Interrupt (SEFI)	Single Event Dielectric Rupture (SEDR)
Single Bit Error (SBE)	Single Event Burnout (SEB)
Multiple Bit Error (MBE)	

- What we have now:
  - CREME96 tool, AP9 model (inner belt protons), SIRE2 (MSSREM)
  - L1 and GEO monitors of solar energetic protons (SEPs) and heavy ions (e.g., ACE/EPAM below)
- ***Gap analysis*** **- What we need going forward:**
  - **Ongoing SEP/heavy-ion observations to feed space weather nowcasting plus climatological model and forensics efforts**
  - **Inner belt statistics are pretty good and it is a very stable population (continued monitoring necessary?), though there are notable variations on its outermost half due to time-variable contribution from SEPs**



Spacecraft Charging Hazards: Internal Charging

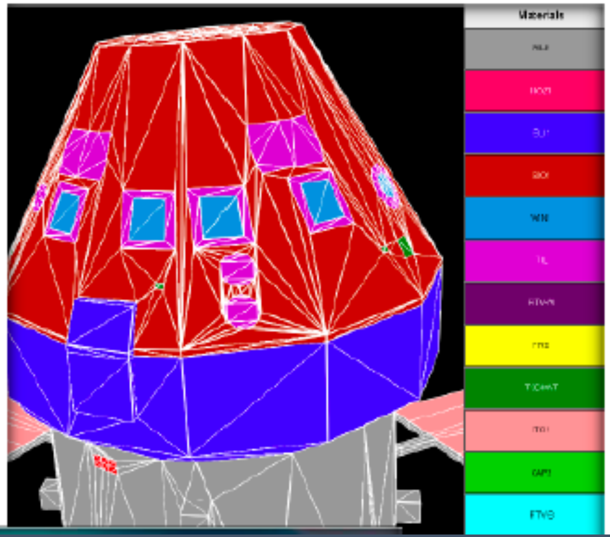


- Internal charging involves charge accumulation in spacecraft internal dielectric materials (e.g., circuit boards and components, cable insulation, MLI layers…), and threat of electrostatic breakdown
- Occurs due primarily to > keV electrons
- Time-integrated effect until breakdown threshold; breakdown anomalies may have no relation to specific events/features in the space environment
- What we have now:
  - Best-practice and “standards” designs combined with materials selections, grounding strategy, and shielding specific to different orbits
  - Relevant shielding properties
  - 1D transport models: e.g., DICTAT, NUMIT; 3D transport models: NUMIT3D (JPL), EMA3D-Internal (EMA), SPIS-IC (ONERA)
- ***Gap analysis*** **- What we need going forward:**
  - **Climatological approach and modeling is critical for this hazard**
  - **Onboard environment (>keV electron; current charge/discharge) monitors; effects can be highly localized, so ideally, each satellite would have monitors**
  - **Continued development of 3D transport models**
  - **Credible and accurate materials properties**

Spacecraft Charging Hazards: Surface Charging

- Similar to internal charging, surface charging is a very challenging threat to deal with:
  - Spacecraft charging occurs due to current balance: each different surface material (incl. dielectrics and non-conductive) must maintain current balance; sudden changes in the environment or buildup past critical thresholds can result in destructive discharge between/across surface elements
  - Internal charging takes place over very long time periods: charge accumulation occurs over days to months and can be accounted for with adequate onboard monitors and climatological models
  - Surface charging takes place very suddenly: charge accumulation and discharge can occur on time scale of seconds given sudden changes in the electron density and characteristic energy (T) in the environment
- What we have now:
  - Some complex, bespoke modeling tools: NASCAP2K, SPIS, MUSCAT
  - Ground testing facilities using electron flood beams (for GEO and MEO) and hollow-cathode or thruster plasmas (for LEO)
- ***Gap analysis* - What we need going forward:**
  - **Hosted sensors on EVERY spacecraft for anomaly triage/resolution**
  - **Improved modeling capabilities and user-friendly tools**
  - **Better climatological models (and space weather prediction?) for energetic particle injections affecting charging environments at MEO, GEO, and cis-Lunar space (magnetotail)**

Orion CM as modelled in NASCAP2K



Scully (2017)

Energetic Particles in LEO (next presentation!)

- Exponential proliferation of satellites in LEO (e.g., SpaceX StarLink > 12,000 LEO s/c): should our prioritization be first and foremost there considering the increased commercial interest/investment of systems in LEO?
- Needed are actionable products for the community (in general, not just LEO), but the “community” may require bespoke solutions for their very different business models, orbits, spacecraft designs, risk postures… solution is likely not one-size-fits-all
- Our radiation environment models continue to be unable to specify the details of the environment below ~1200km altitude (i.e., fully within the drift and loss cones of the radiation belts)
- O3b satellites (20 s/c; internet for the “Other 3 billion” people…) are at 8000 km circular, polar orbits (where does LEO end and MEO begin?)
- NOAA has no plans to monitor radiation in LEO after MetOp…
- ***Gap analysis: We cannot afford to neglect the LEO environment (and it is big and complicated)!***

Summary

- ***What do we need*** (high-priority/not-available; mid-priority/partial-availability; low-priority/available-now):
  - Continued monitoring of critical particle populations to enable forensics capabilities, data-assimilative models, and improved statistics in climatological models:
    - Real-time radiation belt monitor from near-equatorial GEO-transfer orbit (lost capability with end of Van Allen Probes mission)
    - Real-time monitoring of the plasmasphere and plasmapause location (important boundary for surface charging hazard and radiation belt electrons)
    - Real-time, well-distributed monitoring of the radiation and charging environments from polar LEO, preferably from a range of altitudes below ~1200 km
    - Charging (internal AND surface) environment and diagnostic (discharge sensors) monitors on every spacecraft
    - Improved local time distribution of keV to 100s keV electrons around GEO and MEO (only 2-points from GOES available in real time; need many more)
    - SEP monitors at L1 and GEO (already exist; make sure we keep them going)
    - Continue development of climatological models and user-friendly, credible and accurate tools
  - Advanced ground-based modeling and tools:
    - Improved systems for real time anomaly triage and resolution using combination of rapid forensics with active and climatological datasets plus data-assimilative predictive (nowcast more than forecast!) models
    - Bespoke solutions for specific customers' business models, orbits, spacecraft, etc.
    - Good climatological models and user-friendly tools for satellite designers (not all orbits/hazards well-covered – surface charging!)

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