Potential radiation effects on avionics electronics due to TGF

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Possible effects on avionics induced by terrestrial gamma-ray flashes

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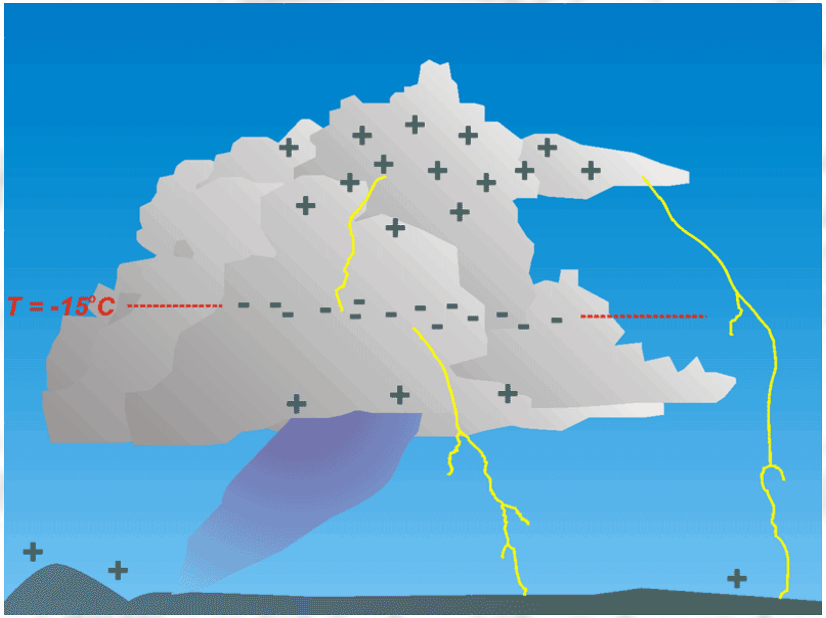
- Radiation from Terrestrial Gamma Ray Flashes
- The (Traditional) Terrestrial Radiation Environment
- Radiation Effects in Electronic Devices
- Do Radiation Effects Really Matter? The Qantas Flight 72 Incident
- Conclusions

Introduction: radiation from thunderstorms

- Thunderclouds and lightings are powerful **particle accelerators**, generating very high-energy electrons, positrons, X rays, and gamma rays
- Associated mostly with **intra-cloud discharges** at altitudes in the range of 10-20 km
- Typical total TGF energy ~ 20kJ



Cartoon: Canadian Forest Service

❖X rays and gamma rays can be remotely measured (through satellites, for instance) to study lighting characteristics

❖ Bright, millisecond-long bursts of gamma rays = **Terrestrial Gamma-Ray flashes (TGFs)**: impulsive atmospheric events characterized by a great acceleration power

- Gamma rays in TGFs come from **the *bremsstrahlung* radiation** of energetic electrons interacting with air
- The electrons are produced by the **relativistic runaway electron avalanche (RRAE)** mechanism, following an energy spectrum with an e-folding energy of about 7 MeV*:*

$$dN/dE \sim exp[-E(MeV)/7\ MeV]$$

independent of the air density, humidity, precipitation, or details about the electric field

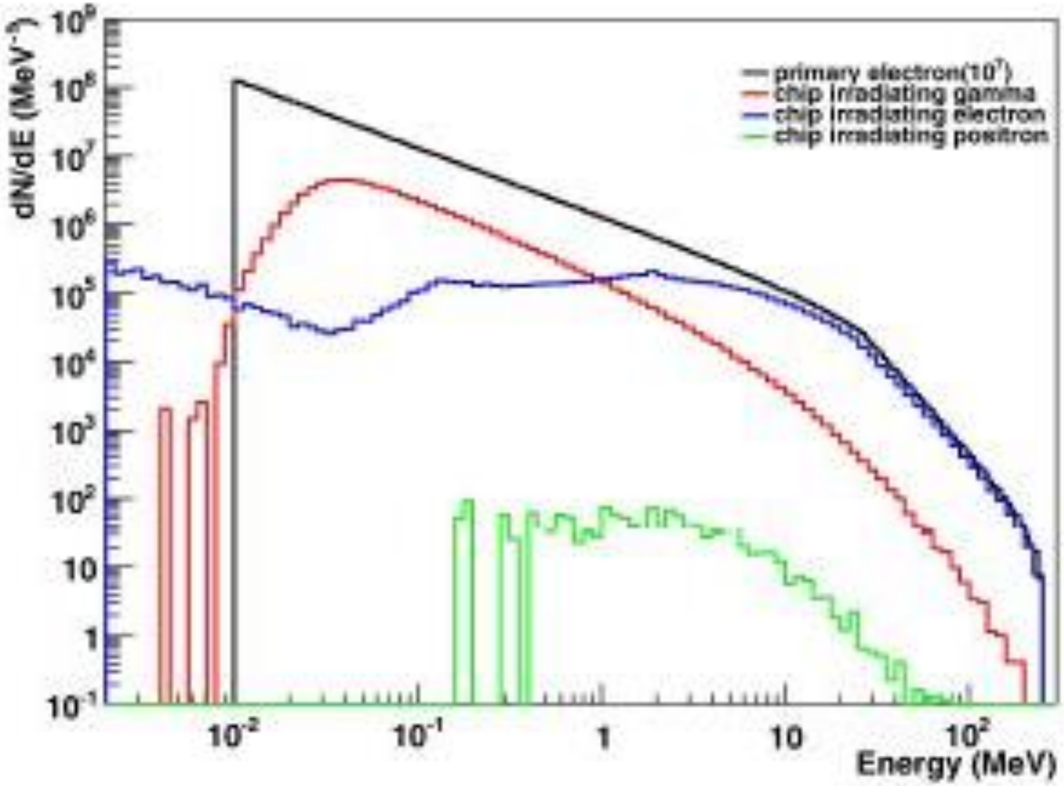
- TGFs & large fluxes of high-energy radiation at about the same altitudes of commercial aircrafts → potential radiation hazards to individuals in aircraft *(Dwyer et al., J. Geophys. Res., 2010)*

→ **Radiation effects on on-board electronics?**

- **Primary electrons/positrons and gamma rays** interact with the aircraft structure and are partially **attenuated and reprocessed by Al, C**, and other heavier elements contained in the aircraft
- A flux of secondary particles and gamma rays propagates inside the aircraft with two main components:
  - **an electromagnetic component** (electrons/positrons and gamma rays)
  - **a neutron component** produced by photoproduction processes

- The **electromagnetic component** inside the aircraft is given by:
  1. primary penetrating electrons/positrons
  2. primary penetrating gamma rays
  3. secondary gamma rays produced by Bremsstrahlung
  4. secondary electrons/positrons produced by gamma ray pair production.

- The **neutron component** inside the aircraft is produced by **photoproduction** processes:
  - Neutrons (n) are produced by energetic gamma rays in the energy range above 15 MeV by the reaction:
    - $\gamma + {}^{27}Al \rightarrow {}^{27}Al^{*} \rightarrow {}^{26}Al + n$
    - where ${}^{27}Al^{*}$ is an excited metastable state of ${}^{27}Al$
  - Similar reactions occur on the other elements of the aircraft structure, and in particular on Carbon composite materials
  - A typical cross-section for these photoproduction reactions is 10^{-2} barn

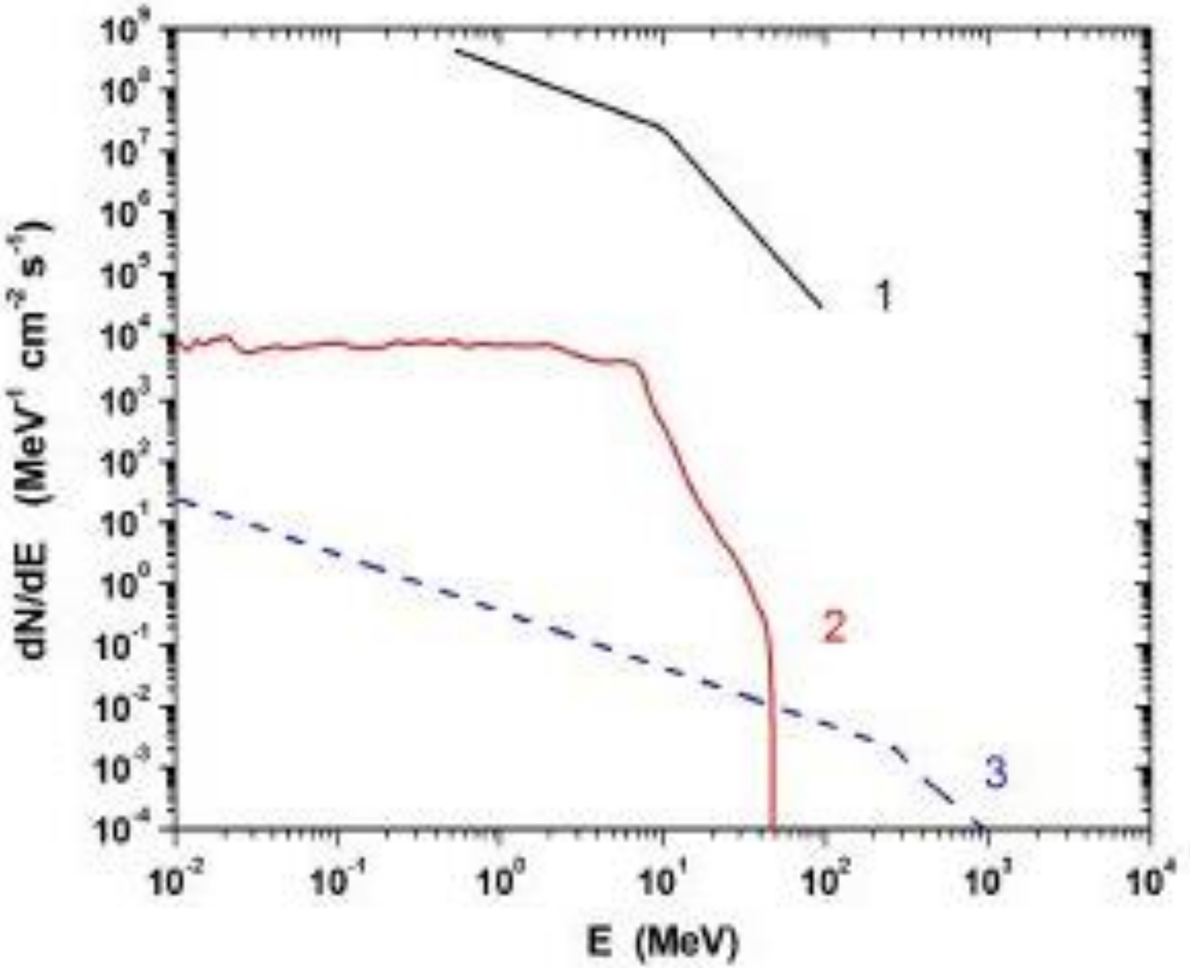


- Spectrum of secondary electromagnetic component
- **Dose:**

  $200\ (\mathrm{rad}) \cdot N_{17} \cdot R_3^{-2}$
- **Dose rate:**

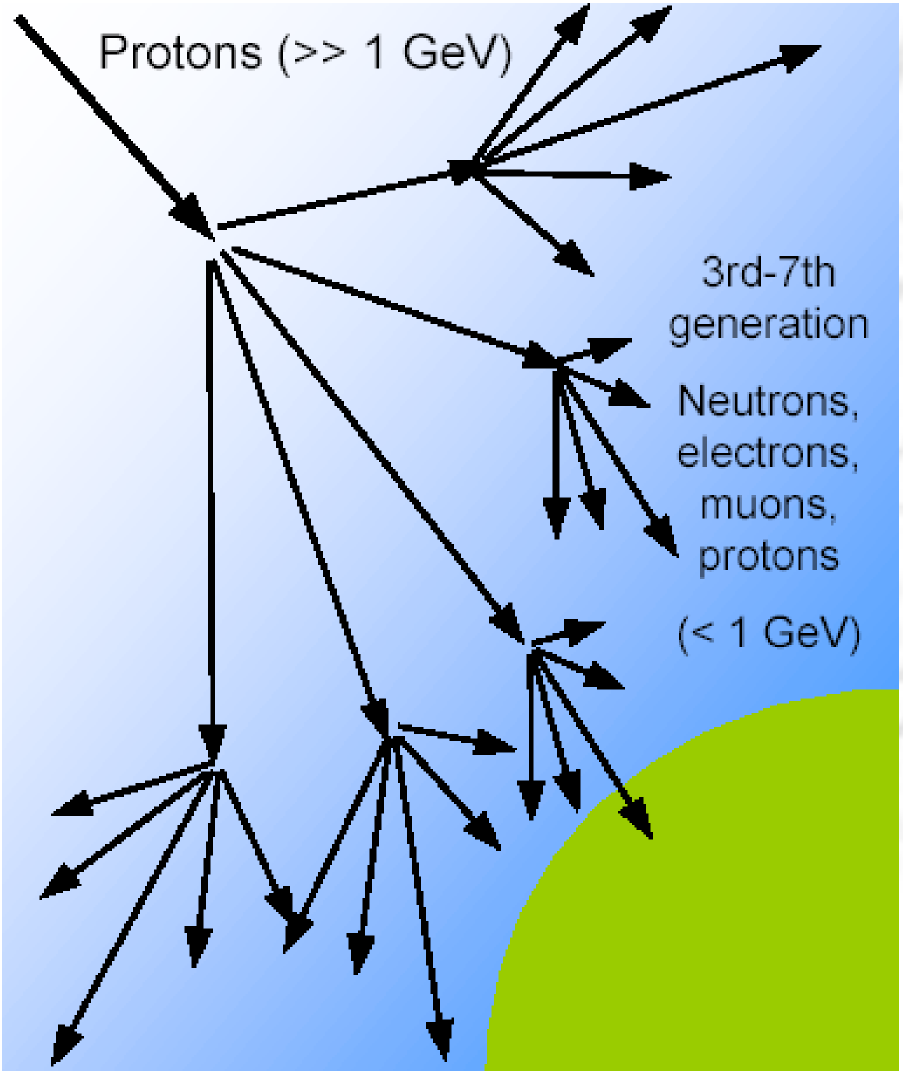
  $2 \cdot 10^7\ (\mathrm{rad} \cdot s^{-1}) \cdot N_{17} \cdot R_3^{-2} \cdot \tau_{-5}^{-1}$

Neutron component



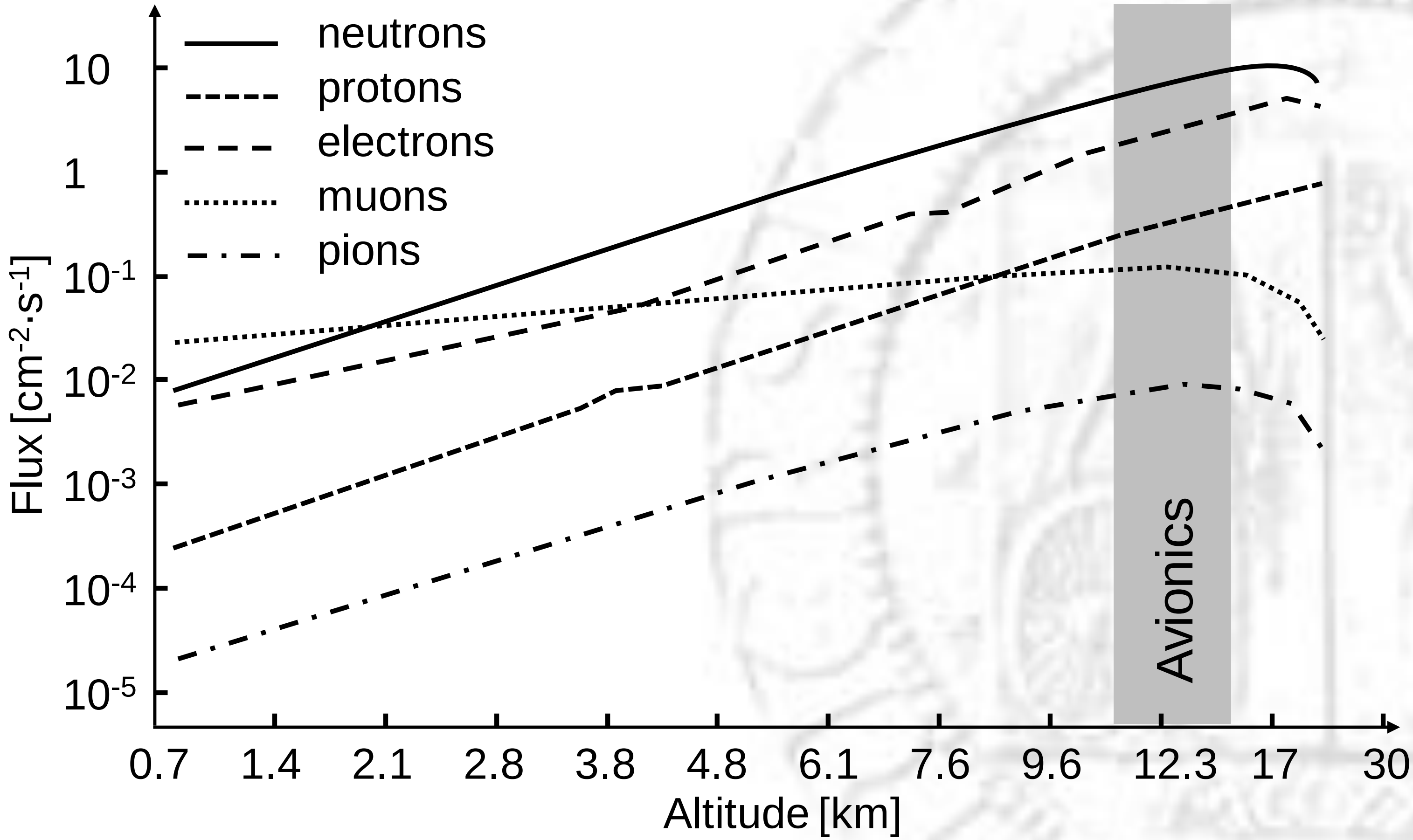
$n \text{ fluence} = 10^7 \cdot cm^{-2} \cdot N_{17} \cdot R_3^{-2} \cdot T_0$

- Example of primary TGF gamma ray spectrum (1)
- Photo-produced neutrons (2)
- Natural neutron spectrum (3)
- A single TGF may produce a neutron fluence 100x higher than that due to the natural background, integrated over a 10 hrs flight



Natural radiation sources from ground level to avionic altitudes, of concern for electronics:

- Byproducts of cosmic rays: atmospheric neutrons (high-energy *(Ziegler and Landford, 1979)* and thermal *(Baumann et al. 1994, 2000)*), protons, electrons, muons
- *Alpha-emitting radioactive contaminants in dice and packages (May and Woods, 1978)*



Avionics:

- Neutron flux is 300x compared to sea level
- Critical systems

- **High energy neutrons** (cosmic ray byproducts, E>1-10 MeV)
  - Indirect interaction through elastic or inelastic nuclear reactions, with generation of recoil nuclei (typically Si) or reaction fragments with high LET
- **Low energy neutrons** (thermal)
  - Indirect interaction via the $^{10}B(n, \alpha)^{7}Li$ nuclear reaction
- **Alpha particles** from radioactive decay of contaminants (from U, Th decay chains) in the chip/package/solder
  - Short range in Si, small LET, direct interaction
- ***Muons****: a possible concern for future technological generations*

Total Ionizing Dose

- affects **dielectric layers** (e.g., gate, isolation, and passivation oxides)
- causes **parametric shifts** in transistors/device parameters
- **cumulative effect**, usually reported as a function of **ionizing dose**

Dose Rate

- affects **semiconductor material** (e.g., bulk Silicon)
- causes chip malfunctioning
- **transient effect**

Displacement Damage

- affects bulk materials (e.g. crystalline Silicon)
- dependent on Non Ionizing Energy Loss (NIEL)
- **cumulative effect**, usually reported as a function of equivalent neutron fluence or displacement dose

Single Event Effects

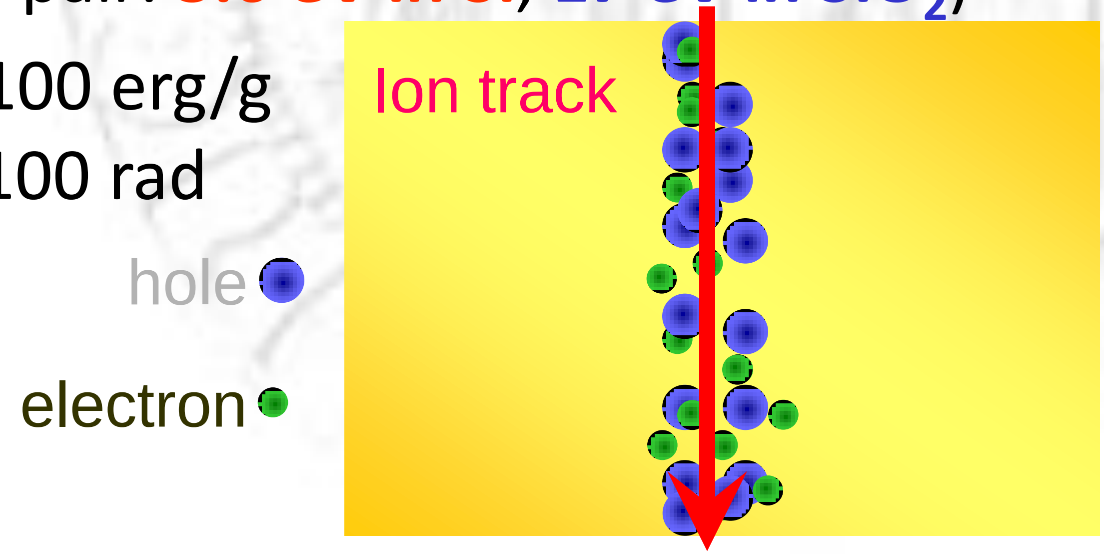
- **stochastic effects:** caused by a single particle impinging randomly on a sensitive device volume
- cause a variety of different effects, **memory corruption, burn-out**, etc.

- **Total I... Dose**
  - affects ... yers (e.g., gate, isolation, and passivation oxides)
  - causes ... **shifts** in transistors/device parameters
  - **cumul...** usually reported as a function of **ionizing dose**
- **Dose R...**
  - affects ... **tor material** (e.g., bulk Silicon)
  - causes ... tioning
  - **transi...**
- **Dis... ...nage**
  - affe... (e.g. crystalline Silicon)
  - depen... ...onizing Energy Loss (NIEL)
  - **cumulati... ...t**, usually reported as a function of equivalent neutron fluence or di... ...lacement dose

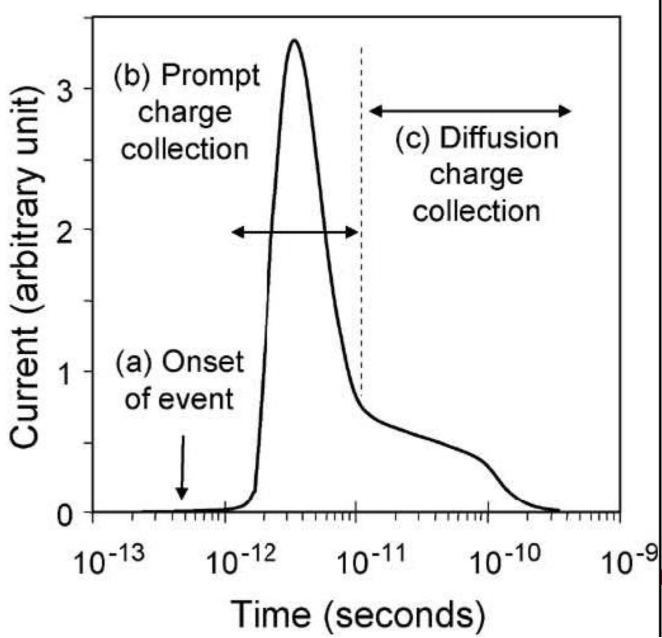
Terrestrial effects

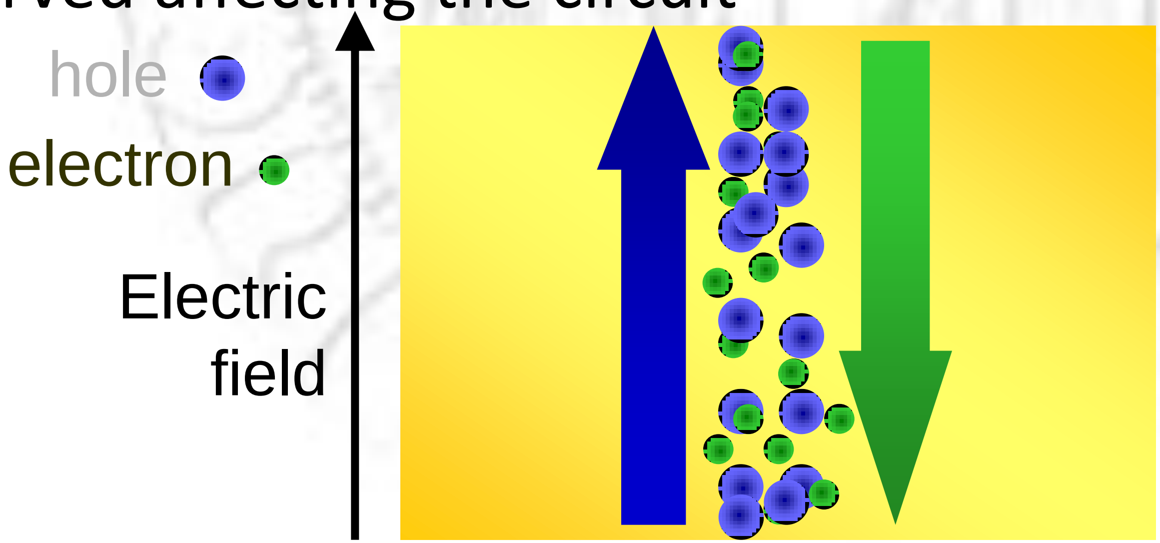
- **Single Event Effects**
  - **stochastic effects:** caused by a single particle impinging randomly on a sensitive device volume
  - cause a variety of different effects, **memory corruption, burn-out**, etc.

- An ionizing particle generates a (dense) track of electron-hole pairs in semiconductors **(Silicon)** and dielectrics **(SiO_2)**
- The number of generated carriers is proportional to the particle **Linear Energy Transfer (LET)** coefficient ($MeVcm^2/mg$), i.e., the ionizing energy loss/unit path length (Energy / e-h pair: **3.6 eV in Si**, **17 eV in SiO_2**)
- Dosimetry: 1 rad = 100 erg/g
  1 Gy = 1 J/kg = 100 rad



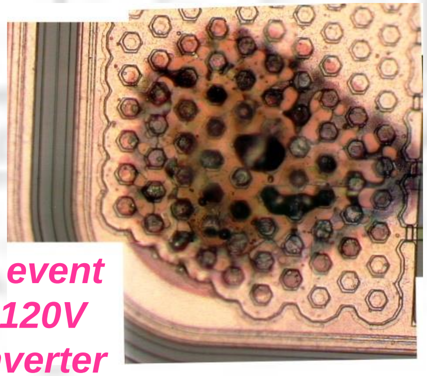
- Under an external electric field the two columns of carriers recombine and drift: many electrons and holes survive in Si, fewer in SiO_2
- Eventually, a net negative/positive charge can be collected at sensitive nodes: if this charge exceeds a threshold value (**critical charge**) an anomalous behavior (**Single Event Effect**) may be observed affecting the circuit





- **Non-destructive (soft errors)**:
  - Single Event Transient (SET)
  - Single Event Upset (SEU)
    - Single Bit Upset (SBU)
    - Multiple Bit Upset (MBU)
  - Single Event Functional Interruption (SEFI)
  - Single Event Latchup (SEL or SELU)… *may be also destructive*
- **Destructive (hard errors)**:
  - Single Event Burnout (SEB)
  - Single Event Gate Rupture (SEGR)
  - Stuck Bits

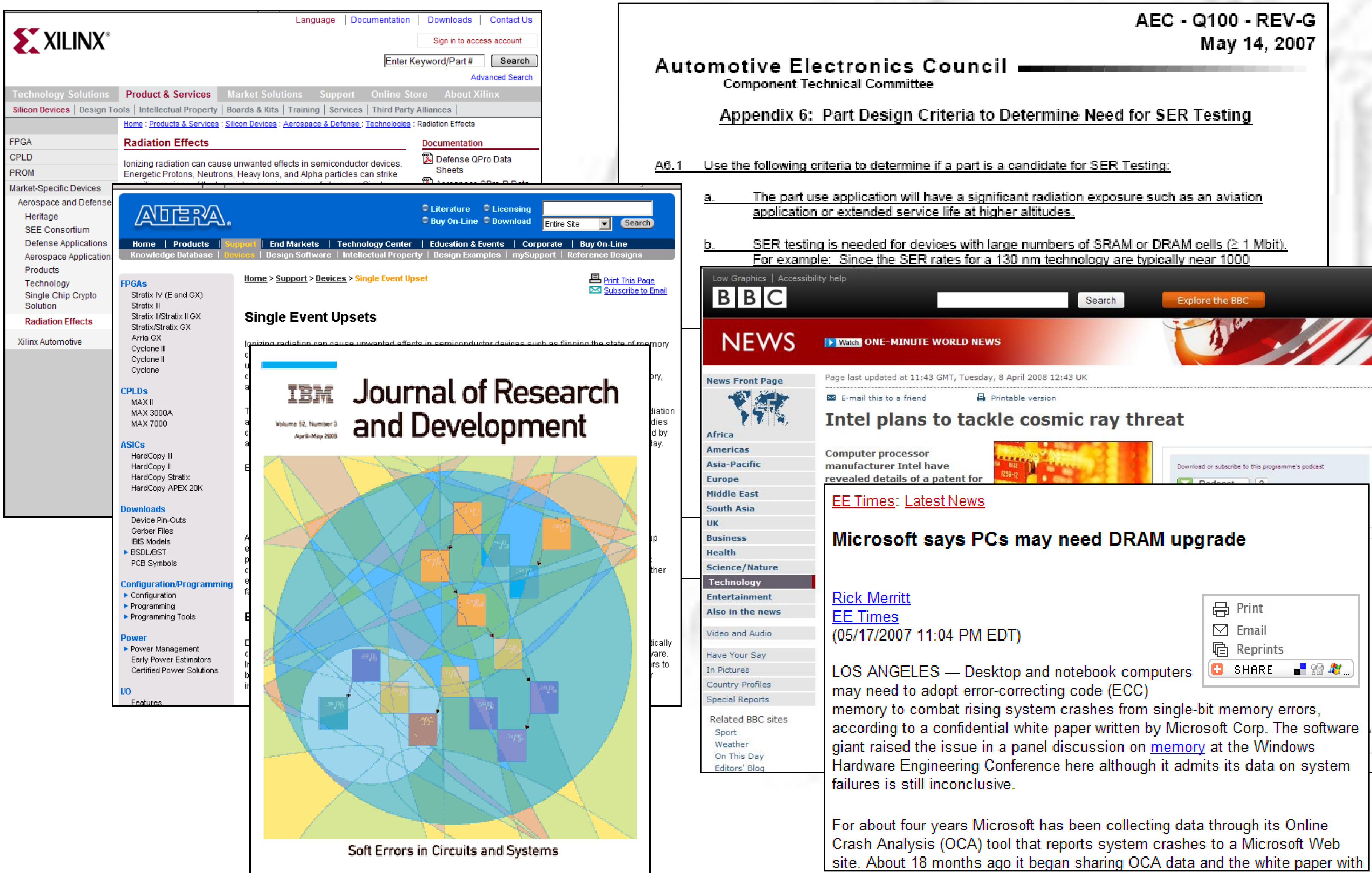
Power devices do not follow down-scaling dimensions and voltages: they exhibit larger sensitivity to neutron-induced effects, even at sea level



Destructive event in a COTS 120V DC-DC Converter

K. LaBel, EWRHE 2004

Do Radiation Effects Really Matter?



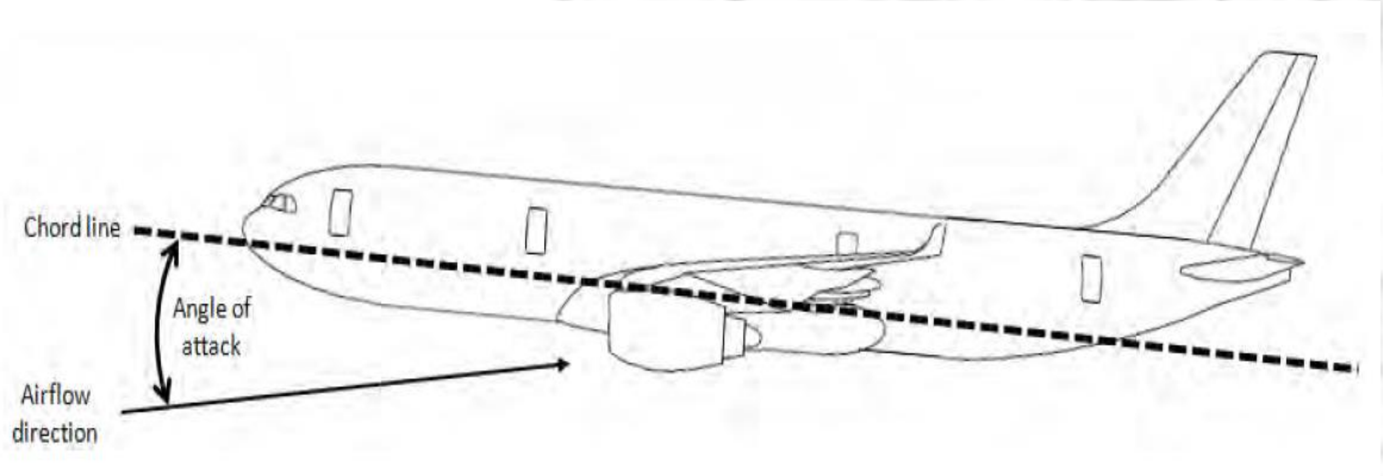
Do Radiation Effects Really Matter? (2)

- Reliability in advanced ICs is improving down to some **10-100 FIT** (1 FIT = 1 failure/10^9 hrs)
- SEE at sea level is dominated by **Soft Errors (SE)** leading to the **Soft Error Rate (SER)** figure of merit; if not properly mitigated, SER may reach **10^5 FIT**
- *"Soft errors have become a huge concern in advanced computer chips because, uncorrected, they produce a failure rate that is higher than all the other reliability mechanisms combined!" - R. Baumann, Fellow, IEEE and TI*
- Evidence of soft errors?
  - many experiments, satellite results, SAA effects, SER reduction after BPSG removal, SER decrease with ULA materials, altitude effects, …

Qantas Flight 72 (QF72) was a scheduled flight from Singapore […] to Perth […] on 7 October 2008 that made an emergency landing […] following an inflight accident featuring a pair of sudden **uncommanded pitch-down manoeuvres** that resulted in serious injuries to many of the occupants

From Wikipedia

"There was a limitation in the algorithm used by the A330/A340 [...] for processing angle of attack (AOA) data. This limitation meant that, in a very specific situation, **multiple** AOA **spikes from only one** of the three air data inertial **reference** units **could result in a nose-down** elevator command."



From ATSB TRANSPORT SAFETY REPORT Aviation Occurrence Investigation AO-2008-070 "In-flight upset 154 km west of Learmonth, WA 7 October 2008VH-QPA Airbus A330-303"

"One of the aircraft's three air data inertial reference units (ADIRU 1) exhibited a **data-spike failure mode**, during which it transmitted a significant amount of incorrect data on air data parameters to other aircraft systems, without flagging that this data was invalid."

"The LTN-101 **air data inertial reference** unit (ADIRU) model had a demonstrated **susceptibility to single event effects** (SEE). The consideration of SEE during the design process was consistent with industry practice at the time the unit was developed, and the overall fault rates of the ADIRU were within the relevant design objectives. "

- *"The failure mode has only been observed three times in over 128 million hours of unit operation, and the unit met the aircraft manufacturer's specifications for reliability and undetected failure rates (the aircraft manufacturer subsequently redesigned the algorithm to prevent the same type of accident). The failure rate 3/0.128 =* ***23.44 FIT*** *is deceiving since the SEU rate at 37,000 feet in unprotected memory will be thousands of times higher – thus the types of "glitches" induced will typically be much higher. What this implies is that the system has a high robustness against glitches (triple redundancy can do that ☺)."*

R. Baumann, 2013

- TGFs produce a new radiation environment, with the simultaneous burst of electromagnetic radiation and neutrons over a short period
- Neutron energy distribution is high enough to activate SEEs in contemporary scaled electronics
- During TGF, the neutron flux is over the expected atmospheric one by several orders of magnitude, becoming comparable to the intensities used in accelerated tests with neutron beams at the accelerators
- Such intensities may challenge the system mitigation capabilities, which were designed to comply with a much less intense neutron flux
- The synergetic effects between neutron and electromagnetic irradiation are unknown: to date, one must deal separately the two components

- The burst of neutrons and electromagnetic radiation associated with strong TGFs may lead to significant increases in the failure probability of avionic systems

- Experimental measurements of the onset of radiation induced effects on onboard electronics, simultaneous to the occurrence of a TGF, would give great insight in a new unexplored natural radiation environment and its impact on flight safety

B. Frankliin, by J.S. Duplessis, 1785, Smithsonian Gallery, Washington, DC, USA

Jupiter, by G.B. Tiepolo, 1757, Villa Valmarana ai Nani, Vicenza, Italy