Notable Predictions about Semiconductor Products or Radiation

- "There is no reason for any individual to have a computer in their home."
  - President of Digital Equipment (1977)
- "a world market for about 5 computers"
  - Founder of IBM (1947)
- the minimum size of a semiconductor device is "within a factor of 2 to 5 ... of devices now being made"
  - 1962 IRE Proceedings
- "X-rays are a hoax."
  - Lord Kelvin (ca. 1900)
Introduction

- Last ~10 years has been a renaissance period for space radiation environment modeling.
  - Growing need to replace long-time standard AP-8 and AE-8 trapped particle models.
  - Interplanetary exploration initiatives driving development of new models of galactic cosmic ray and solar particle event environments.
  - Modern satellite instrumentation leading to unprecedented measurement accuracy/resolution.
  - Pervasive use of commercial-off-the-shelf (COTS) microelectronics requires more accurate predictive capabilities for space applications.

Objectives

- Provide basic understanding of the components of space radiation environment and their variation.
  - trapped protons and electrons
  - galactic cosmic rays
  - solar particle events
- Review traditional radiation effects application models
- Present recent developments
  - Give overview of modeling techniques used
  - Emphasis on probabilistic methods applied to solar particle environment, which may find other radiation effects applications.
  - Compare new model results to traditional models for various orbits, times during solar cycle, etc.

Outline

- The Solar Activity Cycle
- The Earth’s Trapped Radiation Environment
- Galactic Cosmic Rays
- Solar Particle Events
- Future Challenges

The Solar Activity Cycle

- Understanding sun’s approximately 11-year cyclical activity is important aspect of modeling space radiation environment.
  - Typically 7 years solar maximum when activity levels are high
  - Typically 4 years solar minimum when activity levels are low
  - Space radiation intensities vary significantly throughout solar cycle.

To be presented by Michael A. Xapsos at the 2006 IEEE Nuclear and Space Radiation Effects Conference (NSREC),
Outline

1. The Earth's Trapped Radiation Environment
   - The Magnetosphere and Trapped Particle Motion
     - Trapped Proton Models
     - Recent Developments
     - Trapped Electron Models
     - AE-8
     - Recent Developments

2. The Earth's Internal Magnetic Field

3. Trapped Charged Particle Motion
   - Equation of motion for charged particle in magnetic field:
     \[ F = qv \times B \]
   - If field is uniform:
     - 2 dimensions: circular motion
     - 3 dimensions: helical or spiral motion

The Earth's Magnetosphere

- Consists of
  - External magnetic field resulting from solar wind (plasma continually emitted by sun)
  - Internal magnetic field originating primarily from inside the earth
- Extent of magnetosphere
  - 6 to 10 earth radii on sunward side
  - ~1000 earth radii in direction away from sun

Earth's Internal Magnetic Field

- Geomagnetic field is approximately dipolar for altitudes up to about 4 to 6 earth radii.
- Dipole axis not same as geographic North-South axis
  - 1° tilt
  - > 500 km displacement
- Trapped particle populations conveniently mapped in terms of dipole coordinate systems.

Trapped Charged Particle Motion

- In earth's magnetic field
  - Particles spiral along magnetic field lines
- Increased field strength in polar region causes spiral to tighten and eventually direction reversal of particle
- Additionally, there is a slower longitudinal drift around the earth
- A complete azimuthal rotation traces out a drift shell
- L-shell parameter indicates magnetic equatorial distance from center of earth in number of earth radii.

Characteristics of Trapped Protons

- Single trapped proton region
  - L-shell values: 1.1 to 10
  - Energies: up to a few 100's of MeV
    - > 10 MeV energies confined to altitudes below 20,000 km
  - Fluxes: up to ~10^8 cm^{-2}s^{-1}, near L = 1.8
- Near inner edge fluxes are modulated by atmospheric density
  - May vary by factor of 2 to 3 over solar cycle

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Proton Radiation Effects and Metrics

- Total Ionizing Dose (TID) - cumulative damage resulting from ionization (electron-hole pair formation) causing:
  - Threshold voltage shifts
  - Leakage currents
  - Timing skew
- Metric used for TID studies:
  Dose = energy deposited per unit mass of material that comprises sensitive volume
  1 rad = 100 erg/g

Proton Radiation Effects and Metrics

- Displacement Damage - cumulative damage resulting from displacement of atoms in semiconductor lattice structure causing:
  - Carrier lifetime shortening
  - Mobility degradation
  - Charge transfer degradation in imaging devices
- Two metrics used for displacement damage studies:
  Displacement Damage Dose = energy going into displaced atoms (nonionizing energy) per unit mass of material that comprises sensitive volume
  Equivalent Proton Fluences - 10 MeV often-used standard

Trapped Particle Models

- General approach to evaluate the environment
  - Use an orbit generator code to calculate the geographical coordinates (latitude, longitude, altitude) of the spacecraft trajectory.
  - Transform the geographical coordinates to dipole coordinate system in which particle population is mapped.
  - Determine trapped particle environment for the spacecraft.

AP-8 Model

- Eighth version of trapped proton modeling effort led by James Vetle.
- Static map of proton population for:
  - Solar maximum
  - Solar minimum
- Data taken in 1960s and 70s
- Example shown in dipole coordinates:
  - X-axis is distance along geomagnetic equator
  - Y-axis is distance along geodipole axis

South Atlantic Anomaly

- Dominates the radiation environment for altitudes less than about 1000 km.
- Caused by tilt and shift in geomagnetic axis relative to rotational axis.
- Inner edge of proton belt is at lower altitudes south and east of Brazil.

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South Atlantic Anomaly

Recent Developments in Trapped Proton Models

PSB97 Model

- Developed at the Belgian Institute for Aeronomy (BIRA) and the Aerospace Corporation.
- Based on SAMPEX data
  - Broad energy range of 18.5 to 500 MeV
  - Accounts for secular variation of geomagnetic field
    - Center of geomagnetic dipole drifts away from geocenter of earth at ~ 2.5 km/year
    - Magnetic moment decreases with time
  - South Atlantic Anomaly drawn slowly inward toward earth.

CRRESPRO Model

- Based on data collected over 14 month period during solar maximum for L = 1.15 to 5.5.
  - Quiet model based on data collected prior to large geomagnetic storm in March 1991
  - Active model for period after the storm
  - Active model shows formation of second stable proton belt
    - Especially apparent in 20 to 70 MeV energy range

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Trapped Proton Model-1 (TPM-1)
- Developed by Huston; combines many features of LATRM and CRRESPRO.
- Covers altitudes from about 300 km out to geosynchronous for 1.5 to 81.5 MeV protons
- Continuous variation of fluxes over solar cycle with 1 month resolution.

Summary: Trapped Protons
- Recent significant advances include:
  - Accounting for secular variation of geomagnetic field
  - Model of continuous variation of flux levels throughout solar cycle
  - Model of second proton belt after large geomagnetic storm
- A combination of TPM-1 and available SAMPEX data (PSB97) would give a reasonably complete trapped proton model.
- Currently being developed

Model Comparisons for International Space Station Orbit

Characteristics of Trapped Electrons
- Inner Zone
  - \( L = 1 \) to 2.8
  - Energies up to 4.5 MeV
  - Fairly stable population
  - long-term avg. flux:
    up to \( 10^9 \text{ cm}^{-2}\text{ s}^{-1} \text{ MeV}^{-1} \) near \( L = 1.5 \)
- Outer Zone
  - \( L = 2.8 \) to 10
  - Energies up to \( \sim 10 \) MeV
  - Very dynamic
  - long-term avg. flux:
    up to \( 3 \times 10^9 \text{ cm}^{-2}\text{ s}^{-1} \text{ MeV}^{-1} \)
    near \( L = 4.5 \)

Slot region - located in between the 2 high intensity zones; region where fluxes at local minimum during quiet periods

Model Comparisons for Elliptical Orbit

Electron Radiation Effects and Metrics
- TID - similar to that for protons
- Displacement Damage
  - Generally do less damage than protons
  - Metrics similar; 1 MeV equivalent electron fluences are used.
- Charging/Discharging Effects
  - Surface charging caused by low energy
    electrons/plasma
  - Deep dielectric charging caused by high energy electrons
  - Key parameter is potential difference induced by charging between dielectric and conductive surface

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Recent Developments in Trapped Electron Models

POLE Model

Correlation to Disturbance Level

POLE Model

Outer Zone Volatility

Correlation to Disturbance Level

Probabilistic Models

AE-8 Model

Recent Developments in
Trapped Electron Models

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Model Comparisons for Geosynchronous Orbit

Outline

- Galactic Cosmic Rays
  - General Characteristics
    - Models
      - NASA Model (Badhwar and O'Neill)
      - Moscow State University (MSU) Model (Yammik)
        - Used in CREME96
      - California Institute of Technology Model (Davis et al.)

Origin

- Galactic cosmic rays (GCR) are high-energy charged particles that originate outside our solar system.
- Generally believed to be remnants from supernova explosions

Summary: Trapped Electrons

- Recent significant advances include:
  - Long-term, climatological model for geostationary altitudes
  - Accounting for variability of outer zone using
    - Probabilistic models
    - Empirical relations with level of geomagnetic disturbance
  - All of above are important for development of a complete model for trapped electrons.

GCR Properties

- Composed mainly of hadrons
- All naturally occurring elements are components:
  - 87% protons
  - 12% alpha particles
  - 1% heavier ions
- Energies: up to 10^{11} GeV
- Fluxes: 1 to 10 cm^{-2} s^{-1}
**Variation with Solar Cycle**

- Energy spectra tend to peak around 1 GeV/nucleon.
- Fluxes modulated by magnetic field in sun and solar wind
  - High activity solar maximum time period attenuates flux for energies less than about 10 GeV/nucleon.

**GCR Models**

- NASA and MSU models originated independently
  - Both based on theory of solar modulation
- Describes penetration of GCR into heliosphere from outside and transport to near earth
- Solar modulation results in variation of GCR fluxes over solar cycle
- Implementation of solar modulation differs
  - NASA model determines solar modulation from near earth GCR measurements, including ground-based neutron monitors.
  - MSU model uses multi-parameter fits to ultimately relate GCR intensities to observed sunspot numbers.

**GCR Radiation Effects and Metrics**

- Single Event Effects (SEE) – event caused by single incident ion
  - May be caused by direct ionization (usually the case for incident heavy ions)
  - May be caused by nuclear reaction products (usually the case for incident protons)
- Metric commonly used for heavy ion induced SEE is Linear Energy Transfer (LET)
  - LET = energy lost by ionizing particle per unit path length in sensitive volume
  - Path length often expressed as areal density by dividing by material density
  - LET units commonly used are MeV·cm²/mg.

**Comparison of Proton Fluxes**

- Comparison of proton energy spectra for NASA and MSU models with a model from QinetiQ used for atmospheric neutron studies shows:
  - Discrepancies among all models for narrow time ranges
  - Similar predictions for total fluence over course of a solar cycle

**LET Spectra**

**Comparison to ACE Satellite Measurements**

- Availability of ACE satellite data makes possible detailed comparisons not previously possible.
  - Shown are results for 1997 solar minimum time period.
  - MSU model tends to have lower rms deviation.
  - NASA model tends to have more accurate spectral shape.
  - NASA model recently updated using ACE data.
    - Improves on results shown.

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Recent significant advances include:
- Descriptions of solar modulation of GCR fluxes over the course of the solar cycle
- Incorporation of new significant data from ACE satellite
- Use of knowledge of astrophysical processes to help describe GCR composition and energy spectra

Outline
- Solar Particle Events
  - General Characteristics
  - Solar Proton Models
    - Distribution of Event Magnitudes / Maximum Entropy Approach
    - Cumulative Fluences
    - Worst Case Events / Extreme Value Theory
    - Self-Organized Criticality Model
    - Solar Heavy Ion Models

Characteristics of CMEs
- Hadron composition:
  - 96.4% protons
  - 3.5% alpha particles
  - 0.1% heavier ions (not to be neglected)
- Energies: up to ~ GeV/nucleon
- Event magnitudes:
  - > 10 MeV/nucleon integral fluence: can exceed $10^9$ cm$^{-2}$
  - > 10 MeV/nucleon peak flux: can exceed $10^{-4}$ cm$^{-2}$s$^{-1}$
Radiation Effects and Metrics

- TID
  - Dose deposited primarily by protons
- Displacement Damage
  - Caused mainly by protons, possibly significant contribution by alpha particles
- SEE
  - Caused by both protons and heavier ions
- Radiation effects and metrics discussed previously

Solar Particle Event

Distribution of Event Magnitudes

- Since solar particle events are probabilistic in nature, it is important to accurately model the distribution of event magnitudes
- However, the data are limited
  - Makes selecting a distribution difficult and arbitrary
    - Lognormal distributions describe only larger events
    - Power function distributions describe only smaller events
- Use Maximum Entropy Principle
  - Method for making arguably the best selection of a probability distribution compatible with known information

Solar Cycle Dependence

- Maximum Entropy Principle
  - Developed by E. T. Jaynes in studies of statistical mechanics
  - Re-interpreted the field as a form of statistical inference rather than a physical theory
  - Maximizing a probability distribution's entropy, S, subject to known constraints gives least biased distribution in the face of limited data
    \[ S = -\sum p(M) \ln p(M) \, dM \]
  - \( S \) is mathematically equivalent to thermodynamic entropy but is interpreted here as the probability distribution's uncertainty.

Solar Proton Models

- Constraints imposed on the solar proton event magnitude distribution:
  - It can be normalized
  - It has a well-defined mean
  - It has a known lower limit, i.e., detection threshold
  - It is bounded, i.e., no infinitely large events
- Use resulting system of equations along with entropy expression to find distribution \( p(M) \) that maximizes the entropy
  - Has been worked out for many situations
  - Can use Lagrange multiplier technique

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Distribution of Event Magnitudes

- Resulting solution is a truncated power function in the event magnitude for solar maximum
- Describes essential features of the distribution
  - Smaller event sizes follow power function
  - Larger event sizes fall off much more rapidly

Cumulative Fluence During Solar Maximum

- Once the distribution of event fluence magnitudes is known, the cumulative fluence during a mission can be calculated.
- Confidence level approaches are often used
  - Allows designers to evaluate risk-cost-performance tradeoffs for parts

Models for Solar Maximum

- King/Stassinopoulos model for 10 to 100 MeV protons during solar cycle 20
  - Based on Aug 1972 event
- JPL91 model for 1 to 80 MeV protons based on 2.5 solar cycles
  - Uses Monte Carlo simulations
- ESP/PSYCHIC model for 1 to 330 MeV MeV protons based on 3.5 solar cycles
  - Establishes lognormal cumulative distributions and uses compound Poisson process theory.

Worst Case Events

- Spacecraft must be able to survive a worst case solar particle event.
- One approach is to design to a well-known large event, i.e., Oct 1989.
- However, this is a rather arbitrary choice.
- More useful information can be provided if a confidence level based approach is used.
- Can be done with extreme value statistics

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Extreme Value Statistics

- Usual central value statistics characterizes the distribution of random variable by mean value and standard deviation.
- Extreme value statistics focuses on largest (or smallest) values taken on by distribution.
  - Pioneered by E. Gumbel
  - Initially applied to environmental phenomena such as earthquakes, floods
  - Application to device arrays such as CCDs and memories

Worst Case Event Model

- Given the initial probability distribution, extreme value relations can be used to calculate worst case events as function of confidence level and mission duration
  - Peak flux
  - Event fluence
  - Interesting feature is "design limit", a statistical upper limit for event magnitude
    - Consistent with historical evidence such as recent analysis of the 400 year nitrate record in polar ice cores

Self-organized Criticality Model

- General model proposed by P. Bak to describe energy release processes in complex, interactive systems
  - Slow, continuous build-up of energy in system
  - System naturally evolves to critical state
  - Minor, localized disturbance starts energy releasing chain reaction
  - Chain reactions (event sizes) span orders of magnitude
  - Result is "scale invariant" power law distribution of event sizes
  - Because of this basic nature, event magnitudes cannot be accurately predicted
  - Analogous arguments about lack of predictability of times of occurrence of events

Basic Nature of Solar Particle Events

- We have assumed that solar particle events are probabilistic in nature.
  - Especially serious concern for manned missions to moon and Mars
- Organizations such as NASA and ESA have put substantial resources into finding reliable predictors of events
  - Studies of precursor phenomena
  - Key times
- Basic Question: Are deterministic predictions of events possible? In other words, is it possible to predict the time of occurrence and magnitude of solar particle events?
- The Self-Organized Criticality Model has implications for this issue.

Do solar particle events exhibit long-term correlation?
Cumulative Deviation Analysis for 1989 Solar Proton Data

- Type of analysis originated by Hurst in studies of flood and drought periods in region of interest
- Plot indicates water level:
  - Negative slope indicates drought period
  - Rainfall results in sudden increase
- Application to solar proton data:
  - Solar proton "droughts"
  - Event occurrence causes sudden increase

Rescaled Range Analysis 1989 Data

- The power index or Hurst Coefficient, R, indicates the amount of correlation between events:
  - $R = 0.5$ → uncorrelated
  - $R = 0.8$ → correlated
- Typically, $0.7 < R < 0.8$ for correlated natural phenomena
- $H = 0.70$ for solar proton events
- Solar proton events exhibit long-term correlation
  - Can be interpreted as due to energy storage and release mechanism in corona
  - Consistent with SOC phenomenon

Fractal Properties

The basic nature does not change when viewed on a different scale. It is "scale invariant", "self-similar" or "fractal".

Integral Distribution of Fluence Magnitudes: 1973 - 2001

- Density function (slope) is exactly proportional to the reciprocal of the fluence:
  - It is a power function
  - 1/ff or flicker noise
  - Dynamics of system strongly influenced by past events
  - Reinforces conclusions of rescaled range analysis

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Self-Organized Criticality Model

- Based on 28 years of data, there is strong evidence that solar particle events are a self-organized critical phenomena.

- Implications:
  - Deterministic prediction of events is precluded.
  - Physically based model would deal with energy storage and release processes in solar structure
  - A strategy to deal with the solar particle environment for manned missions to moon and Mars should involve establishing a measurement system in inner heliosphere for early detection and warning of events.

Solar Heavy Ion Models

- Not as advanced as solar proton models due to relative lack of data
  - Large number of heavy ion species complicates measurements

- Cumulative fluences:
  - Preliminary model by Tylka for 2 energy bins each of He, CHO, group and Fe
  - PSYCHIC model of NASA GSFC
    - Statistical model of 1 to 100 MeV/nucleon He based on 26 years of data from IMP-8 and GOES
    - Other major elements C, N, O, Ne, Mg, Si, S and Fe determined by 7 years of data from ACE
    - Minor elements scaled according to abundance model

Future Challenges

- Generally we should strive to produce more dynamical and more physical models.
  - Increased understanding should result in more accurate projections for future missions

- Trapped particle model challenges:
  - Initially more detailed maps for various climatological conditions that occur throughout solar cycle
  - Ultimately an accurate description of source and loss mechanisms of trapped particles is needed.

Solar Heavy Ion Models

- Worst case event models:
  - MACREE based on October 1989 event measurements for protons and alphas; modification of CREME86 abundance model for heavier elements
  - JPL Model based on 18 years of 1 to 30 MeV/nucleon alpha particle data and abundance model for heavier elements
  - CREME96 Model using October 1989 event; it is noteworthy this includes measurements of C, O and Fe that extend out to ~ 1 GeV/nucleon
    - Peak flux, worst day, worst week

Future Challenges

- GCR model challenges:
  - Continue to improve description of solar modulation potential
  - Merge together models of astrophysical processes describing GCR transport in galaxy with current solar modulation models

- Solar particle event model challenge:
  - Describe energy storage and release process in solar structure

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Future Challenges

- Lack of predictability of future solar cycle activity is a serious concern
  - Occasional large drops in solar activity are seen from one cycle to the next. This results in substantial increase in GCR exposure, which is a major issue for manned missions.

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