IEEE NSREC Short Course Session I

Modeling the Space Radiation Environment

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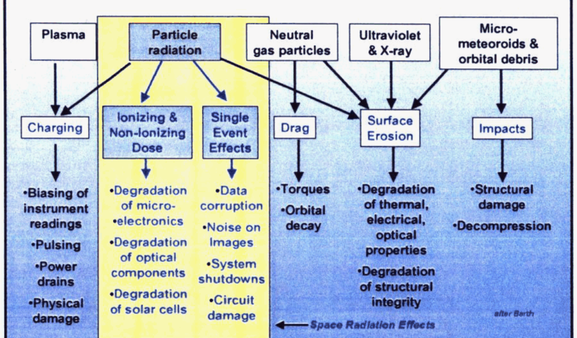
- NASA Living With A Star TR&T Program

"Prediction is very difficult, especially if it's about the future."

- Niels Bohr

Space Environments and Effects



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

- The radiation environment must be understood and accurately modeled.
  - reliable, cost-effective designs
  - implement new space technologies
- Underestimating radiation levels leads to
  - excessive risk
  - degraded system performance
  - loss of mission lifetime
- Overestimating radiation levels leads to
  - excessive shielding
  - reduced payloads
  - increased cost

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

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

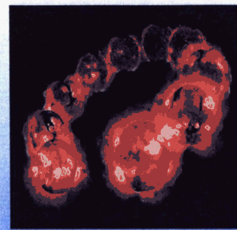
- Provide basic understanding of the components of space radiation environment and their variation.
  - trapped protons and electrons
  - galactic cosmic rays
  - solar particle events
- Review traditional radiation effects application models
- Present recent developments
  - Give overview of modeling 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

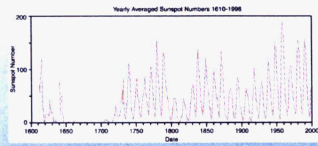
The Solar Activity Cycle

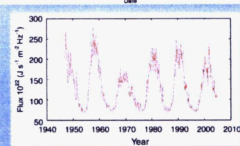
- Understanding sun's approximately 11-year cyclical activity is important aspect of modeling space radiation environment.
  - Typically 7 years solar maximum when activity levels are high
  - Typically 4 years solar minimum when activity levels are low
- Space radiation intensities vary significantly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



The Solar Activity Cycle

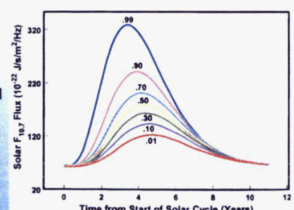
- Common indicators of solar activity





The Solar Activity Cycle

- Forecasting a cycle's activity after its beginning often done with regression techniques.
- Forecasting before its beginning has had minimal success.
- Suggests probabilistic methods are useful
  - Cycle is asymmetric, with longer descending phase.
  - The greater the activity, the faster the rise time to peak level.



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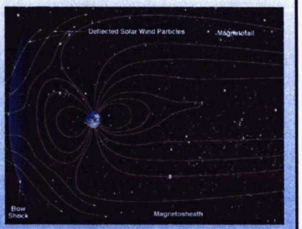
Outline

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

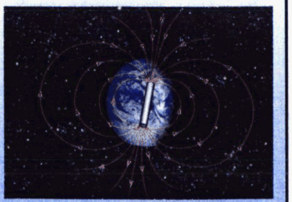
The Earth's Magnetosphere

- 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



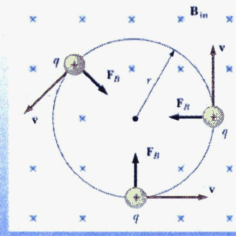
Earth's Internal Magnetic Field

- Geomagnetic field is approximately dipolar for altitudes up to about 4 to 5 earth radii.
- Dipole axis not same as geographic North-South axis
  - 11° tilt
  - > 500 km displacement
- Trapped particle populations conveniently mapped in terms of dipole coordinate systems.



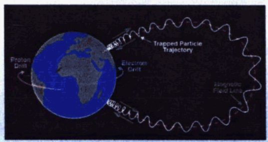
Trapped Charged Particle Motion

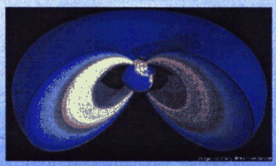
- Equation of motion for charged particle in magnetic field:
  F = qv x B
- If field is uniform:
  - 2 dimensions – circular motion
  - 3 dimensions – helical or spiral motion



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: 1.15 to 10
  - Energies: up to a few 100's of MeV
    - > 10 MeV energies confined to altitudes below 20,000 km
  - Fluxes: up to ~ 10^5 $cm^{-2}s^{-1}$, near L = 1.8
- Near inner edge fluxes are modulated by atmospheric density
  - May vary by factor of 2 to 3 over a solar cycle

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 skews
- 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

Proton Radiation Effects and Metrics

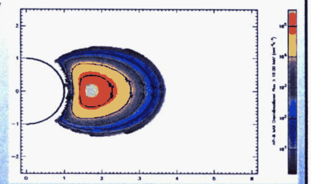
- Single Event Effects (SEE) – event caused by single incident proton
  - Non-destructive – SEU, SET, MBU, SHE
  - Destructive – SEL, SEGR, SEB
- Results commonly presented as function of incident proton energy
  - Most SEE result from nuclear reaction products, which are influenced significantly by incident proton energy.

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.

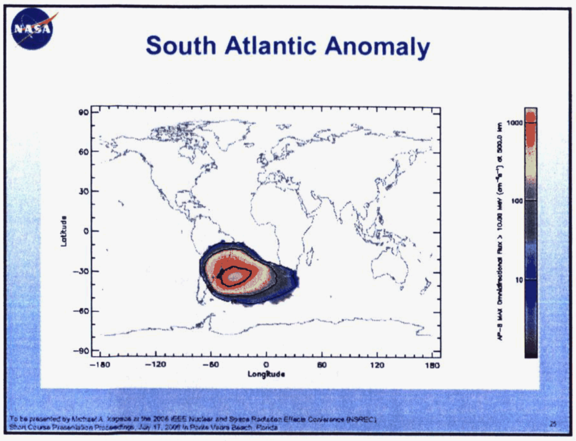
AP-8 Model

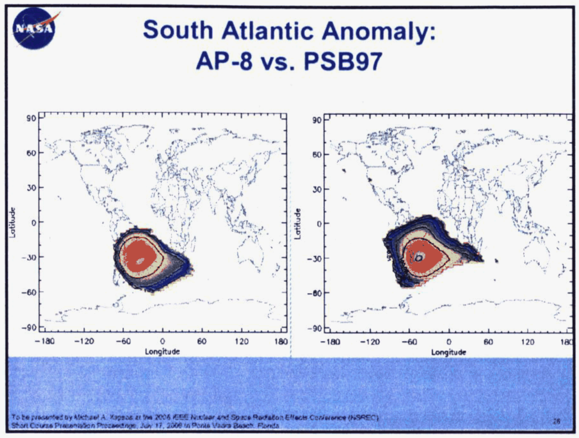
- Eighth version of trapped proton modeling effort led by James Vette.
- Static map of proton population for
  - Solar maximum
  - Solar minimum
- Data taken in 1960s and 70s
- Example shown in dipole coordinates
  - X-axis is distance along geomagnetic equator
  - Y-axis is distance along geodipole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

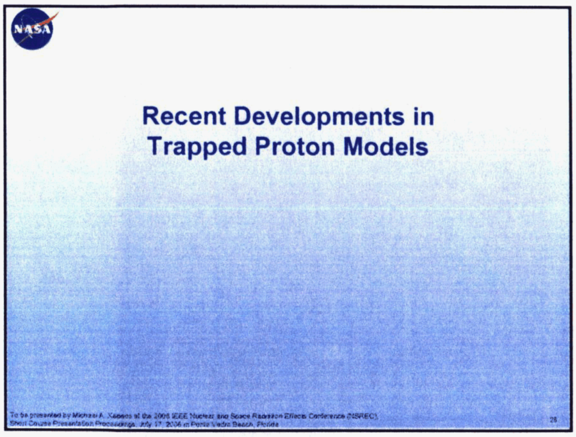


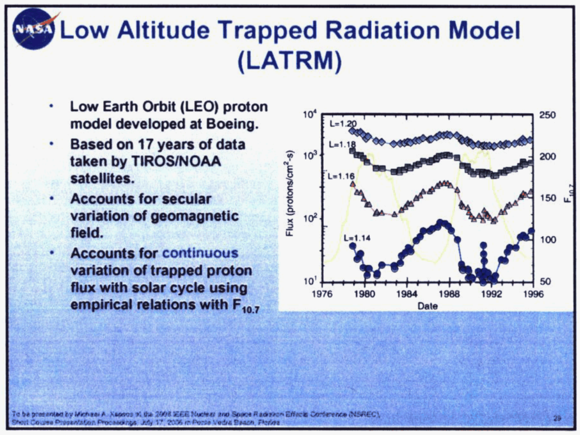
South Atlantic Anomaly

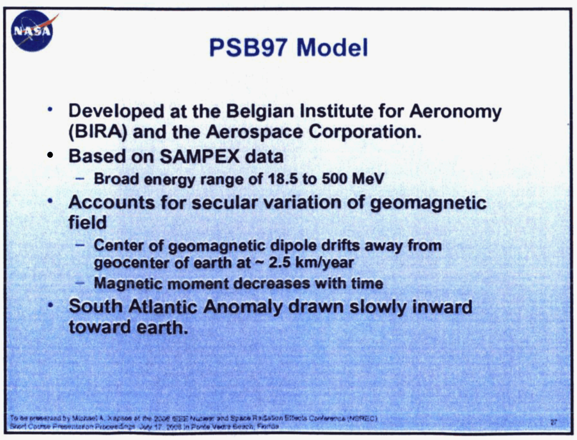
- Dominates the radiation environment for altitudes less than about 1000 km.
- Caused by tilt and shift in geomagnetic axis relative to rotational axis.
- Inner edge of proton belt is at lower altitudes south and east of Brazil.

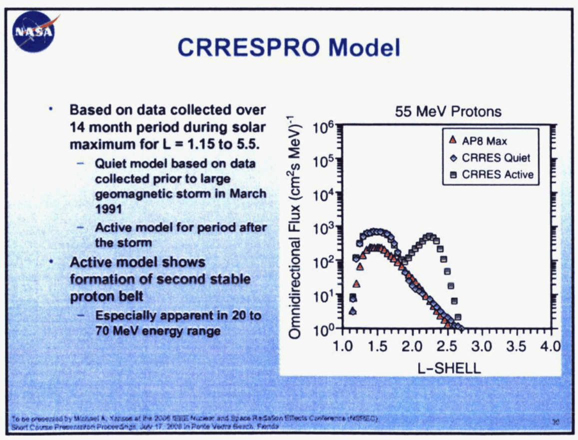












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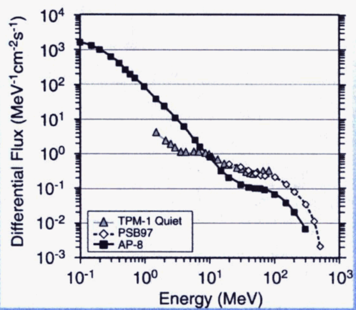
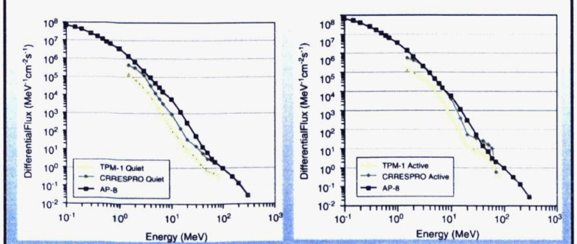
Trapped Proton Model-1 (TPM-1)

- 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.

Model Comparisons for International Space Station Orbit



Model Comparisons for Elliptical Orbit



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

Characteristics of Trapped Electrons

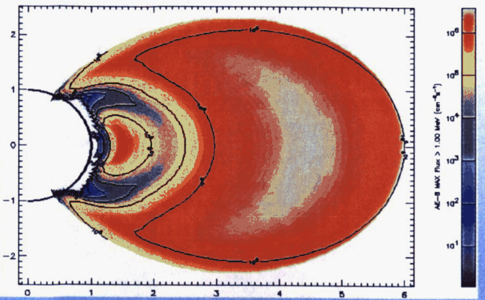
- Inner Zone
  - L = 1 to 2.8
  - Energies up to 4.5 MeV
  - Fairly stable population
  - long-term avg. flux: up to 10^6 $cm^{-2}s^{-1}$ (> 1 MeV) near L = 1.5
- Outer Zone
  - L = 2.8 to 10
  - Energies up to ~ 10 MeV
  - Very dynamic
  - long-term avg. flux: up to 3×10^6 $cm^{-2}s^{-1}$ (> 1 MeV) near L = 4.5

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

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.

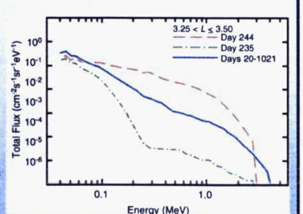
AE-8 Model



Recent Developments in Trapped Electron Models

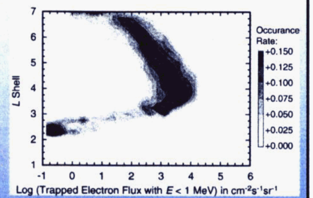
Outer Zone Volatility

- Inner zone often dominated by trapped protons.
- Outer zone often dominated by trapped electrons.
- Recent trapped electron modeling efforts focus on outer zone
  - Features highly dynamic behavior
  - Caused by geomagnetic storms and substorms, which perturb geomagnetic field
  - Results in injection and redistribution of trapped electrons



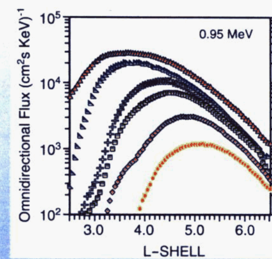
Probabilistic Models

- Indicate both average flux value and its variation for assessing worst case situations
- Model for > 1 MeV electrons based on data from UARS during declining phase of solar cycle 22
  - Highest fluxes for L = 3.5 to 4.5
  - Slot region (L = 2 to 3) shows mostly low fluxes but high variability



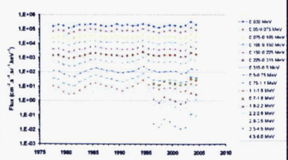
Correlation to Disturbance Level

- CRRESELE Model:
  - Electron energy spectra measured during CRRES mission separated according to Ap index
    - Ap index is measure of general level of global geomagnetic disturbance
  - Spectra in same Ap index range were summed.
  - More disturbed conditions result in higher fluxes.

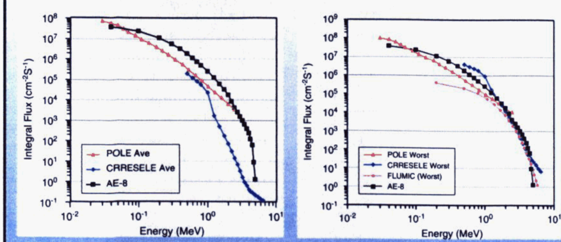


POLE Model

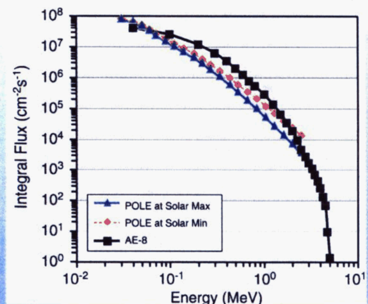
- Developed by ONERA and Los Alamos
- Long-term model of geostationary environment
- Recent update:
  - Based on 28 years of Los Alamos satellite data
  - Energy range is 30 keV to 5.2 MeV
    - Higher energy electrons tend to reach peak fluxes during declining phase of solar maximum.



Model Comparisons for Geosynchronous Orbit



Model Comparisons for Geosynchronous Orbit



Summary: Trapped Electrons

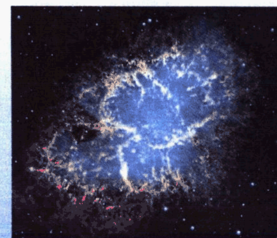
- Recent significant advances include:
  - Long-term, climatological model for geostationary altitudes
  - Accounting for variability of outer zone using
    - Probabilistic models
    - Empirical relations with level of geomagnetic disturbance
- All of above are important for development of a complete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

Outline

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

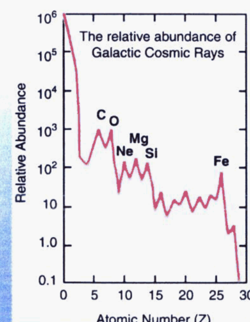
Origin

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



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 $cm^{-2}s^{-1}$



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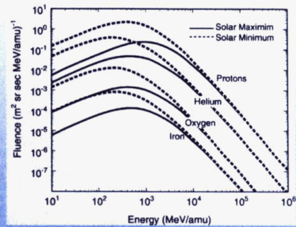
Variation with Solar Cycle

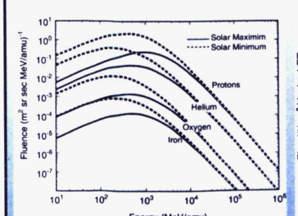
- Energy spectra tend to peak around 1 GeV/nucleon.
- Fluxes modulated by magnetic field in sun and solar wind
  - High activity solar maximum time period attenuates flux for energies less than about 10 GeV/nucleon.

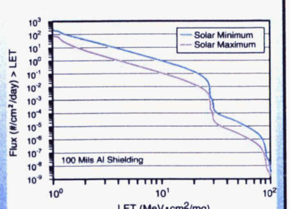


GCR Radiation Effects and Metrics

- 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.

LET Spectra



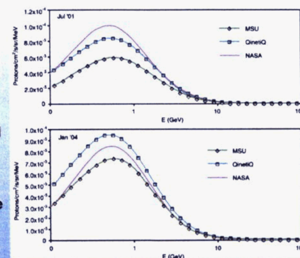


GCR Models

- 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.

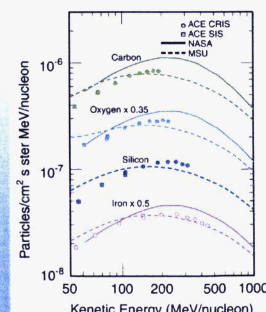
Comparison of Proton Fluxes

- 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



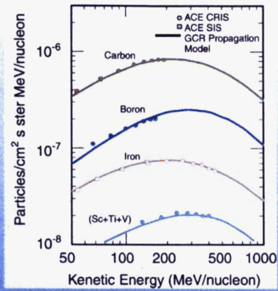
Comparison to ACE Satellite Measurements

- 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



California Institute of Technology Model

- Recent approach is to use transport model of GCR through the galaxy
  - Knowledge of astrophysical processes determine composition and energy spectra
  - Subsequent transport process to near earth (not yet implemented)
  - C and Fe are GCR primaries
  - B, Sc, Ti and V are GCR secondaries produced by fragmentation of primaries on interstellar H and He.



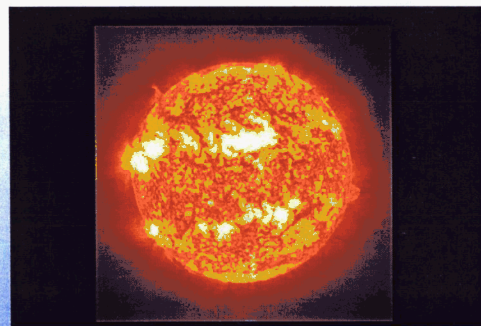
Types of Solar Particle Events

- Solar Flares
  - Occur when localized energy storage in coronal magnetic field becomes too great and burst of energy is released
  - Electron rich
  - Unusually high ^{3}He content relative to ^{4}He
  - Last for hours
- Coronal Mass Ejections (CMEs)
  - Large eruption of plasma that drives a shock wave outward and accelerates particles
  - Proton rich
  - Small ^{3}He content relative to ^{4}He
  - Last for days
- Responsible for major disturbances
  - Interplanetary space
  - In earth's magnetosphere

Summary: GCR Models

- 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

Coronal Mass Ejection



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

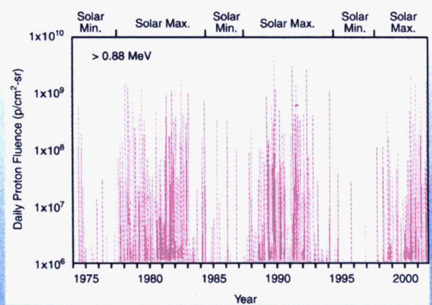
Characteristics of CMEs

- 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 10^5 cm^{-2}s^{-1}

Solar Particle Event 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 Cycle Dependence



Solar Proton Models

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

Distribution of Event Magnitudes

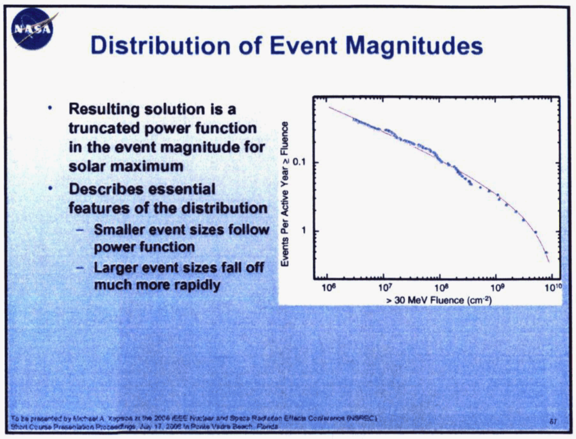
- Maximum Entropy Principle
  - Developed by E. T. Jaynes in studies of statistical mechanics
    - Re-interpreted the field as a form of statistical inference rather than a physical theory
  - Maximizing a probability distribution's entropy, *S*, subject to known constraints gives least biased distribution in the face of limited data

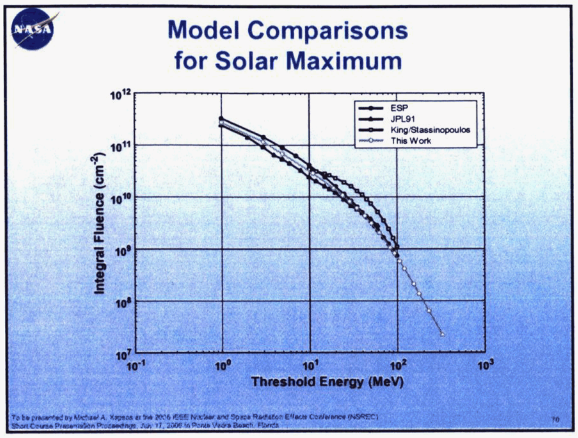
$$S = -\sum p(M)\ln[p(M)]dM$$

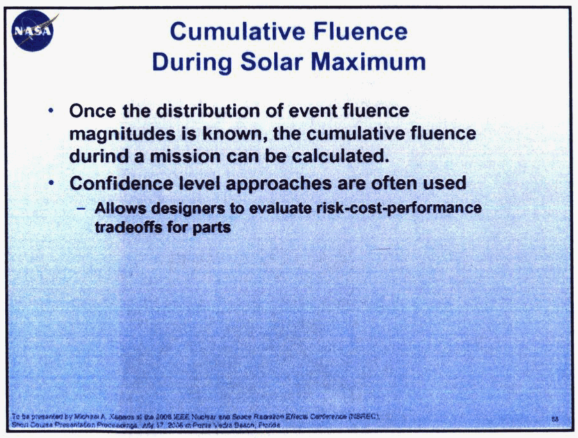
  - *S* is mathematically equivalent to thermodynamic entropy but is interpreted here as the probability distribution's uncertainty.

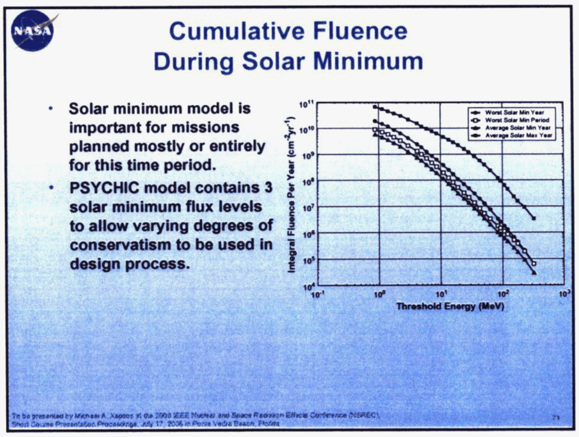
Distribution of Event Magnitudes

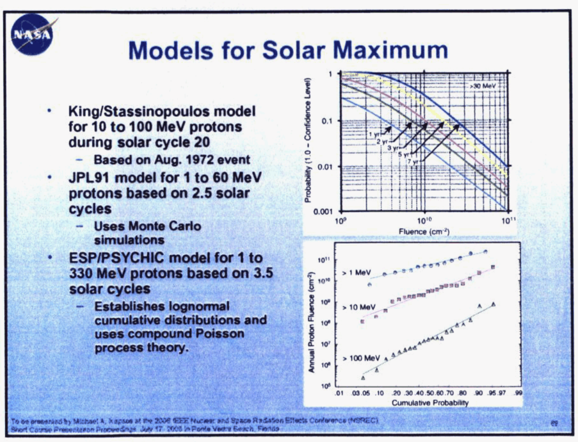
- Constraints imposed on the solar proton event magnitude distribution:
  - It can be normalized
  - It has a well-defined mean
  - It has a known lower limit, i.e., detection threshold
  - It is bounded, i.e., no infinitely large events
- Use resulting system of equations along with entropy expression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

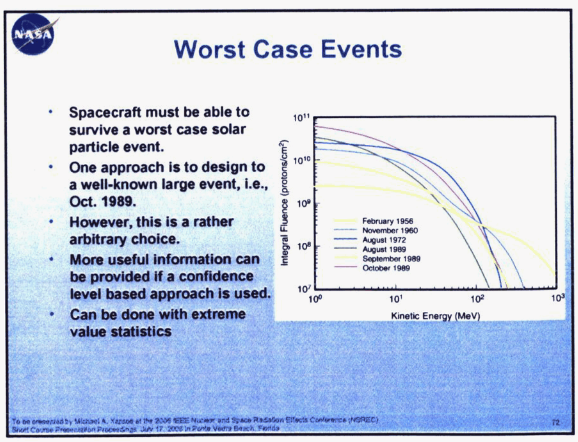












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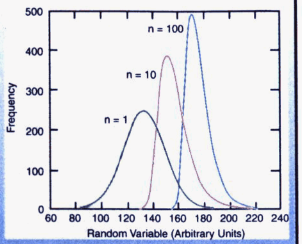
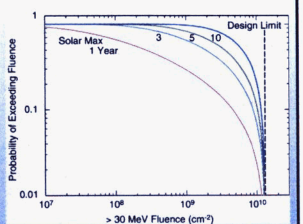
Extreme Value Statistics

- 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



Basic Nature of Solar Particle Events

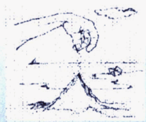
- We have assumed that solar particle events are probabilistic in nature.
  - Especially serious concern for manned missions to moon and Mars
- Organizations such as NASA and ESA have put substantial resources into finding reliable predictors of events
  - Studies of precursor phenomena
    - Magnetic topology signatures
    - X-ray flares
- 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.

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

Self-Organized Criticality Model

- Classic illustrative example is the "sandpile"

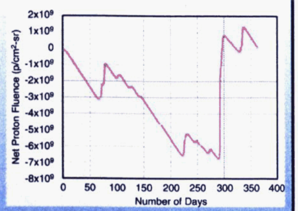


- Features of systems that exhibit self-organized criticality
  - Events show long-term correlation
  - Event sizes exhibit fractal properties
  - Event sizes characterized by power function distribution

Do solar particle events exhibit long-term correlation?

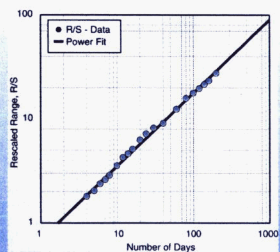
Cumulative Deviation Analysis for 1989 Solar Proton Data

- Type of analysis originated by Hurst in studies 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



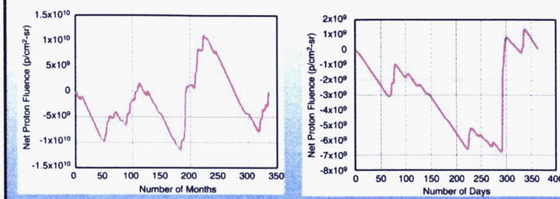
Rescaled Range Analysis 1989 Data

- The power index or Hurst Coefficient, H, indicates the amount of correlation between events
  - H = 0.5 → uncorrelated
  - H > 0.5 → correlated
- Typically, 0.7 < H < 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



Do solar particle event properties exhibit fractal characteristics?

Fractal Properties

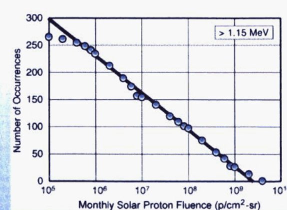


The basic nature does not change when viewed on a different scale. It is "scale invariant", "self-similar" or "fractal".

Is the distribution of fluences for a given time interval a power function?

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/f 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.

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

- 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, CNO group and Fe
  - PSYCHIC model of NASA GSFC
    - Statistical model of 1 to 100 MeV/nucleon He based on 28 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

- 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

Solar Heavy Ion Models

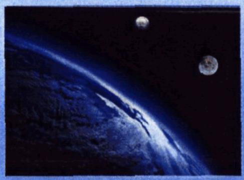
- Worst case event models:
  - MACREE based on October 1989 event measurements for protons and alphas; modification of CREME86 abundance model for heavier elements
  - JPL Model based on 18 years of 1 to 30 MeV/nucleon alpha particle data and abundance model for heavier elements
  - CREME96 Model using 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

- Planning and implementing strategies for manned and robotic missions for new interplanetary exploration initiatives must be done to an unprecedented degree.
- Lack of predictability of solar particle events is a serious concern
  - Establish measurement system in inner heliosphere for early detection of events.
  - Once detected accurate predictions of properties such as arrival time, duration, intensity and energy spectrum must be made for earth, Mars and possibly beyond.

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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