Space radiation environment models: current status and future developments, and integration with Geant4 based analysis tools

D. Heynderickx
DH Consultancy, Leuven, Belgium
P. Nieminen, G. Santin
ESA/ESTEC, Noordwijk, The Netherlands
P. Truscott
QinetiQ Ltd, Farnborough, UK

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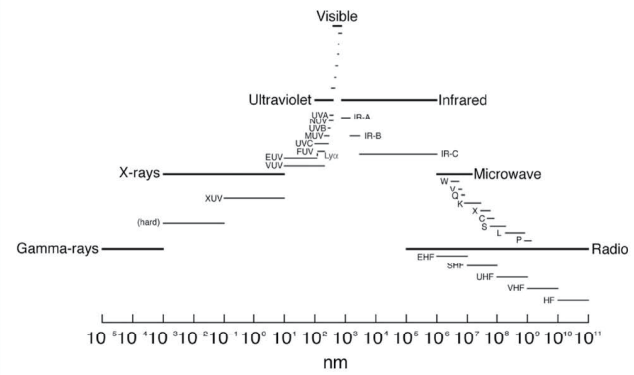
- The space radiation environment: geospace, interplanetary, planetary
- Radiation environment models:
  - Current status
  - Ongoing and future modelling work
  - Model functionality
- Usage of radiation models in Geant4 tools
- Integrated platform for radiation analysis: SPENVIS
- Geant4 implementation issues from a user standpoint

Space radiation environment

- Interplanetary
  - Cosmic rays
  - Solar energetic particles
  - Solar wind particles
  - Solar EM radiation
- Near-Earth environment
  - Penetration of CR and SEP into magnetosphere
  - Radiation belts
- Other planetary bodies

Solar electromagnetic spectrum

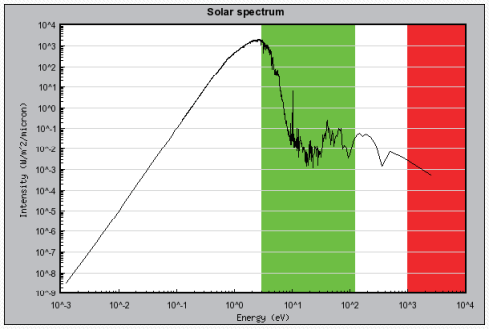
- Spectrum standard: ISO TC20/SC14/WG4 21348



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Solar electromagnetic spectrum

- Daily spectra: http://www.spacewx.com/data/
- X-ray flares: C, B, M, X

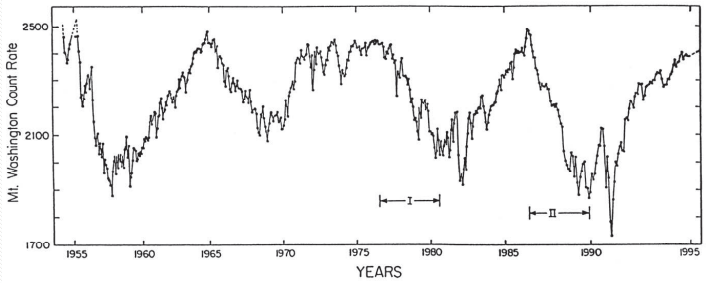


Interplanetary: Cosmic Rays

- Galactic Cosmic rays
  - Fermi acceleration by supernova shock-wave remnants
  - Fully ionized, all ions from H to U, very high energies (up to 10^{20} eV/nuc)
- Anomalous Cosmic Rays
  - neutral interstellar gas that drifts into the heliosphere, becomes singly-ionized near the sun and is then convected to outer heliosphere where accelerated to higher energies
  - Not fully ionized, selected ions (H, He, N, O, Ne, Ar), moderate energies (≤ 100 Mev/nuc)

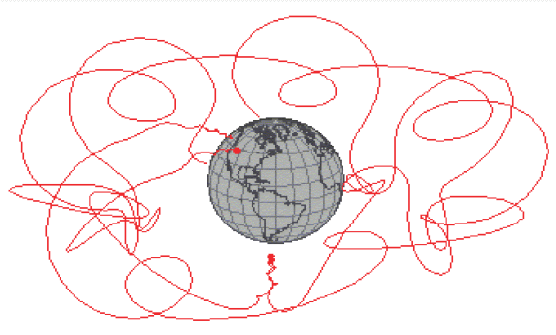
Interplanetary: Cosmic Rays

- Fluxes are anti-correlated with solar cycle due to Forbush decreases
- Standard GCR model correlates with sunspot number



Interplanetary: Cosmic Rays

- Complex trajectories in planetary magnetospheres
- Geomagnetic transmission has to be calculated (e.g. MAGNETOCOSMICS code)



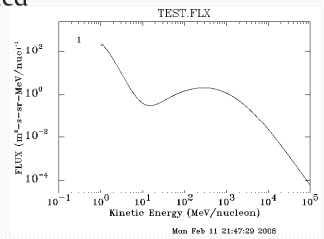
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Interplanetary: Cosmic Rays

- Galactic Cosmic Ray models
  - ISO TC20/SC14/WG4 standard 15390: INP/MSU model (R. Nymmik)
    - Energy range: 10 MeV/nuc - 100 GeV/nuc
    - Implemented in CREME96: https://creme96.nrl.navy.mil/
    - ECSS-E-10-04 standard model
    - ISO standard document and tables have been coded into Fortran by BIRA for implementation in SPENVIS: SUBROUTINE GCR(PARTICLE,TIME,ENERGY,FI,SFI)
  - Older models
    - CREME86
    - Badhwar & Konradi

Interplanetary: Cosmic Rays

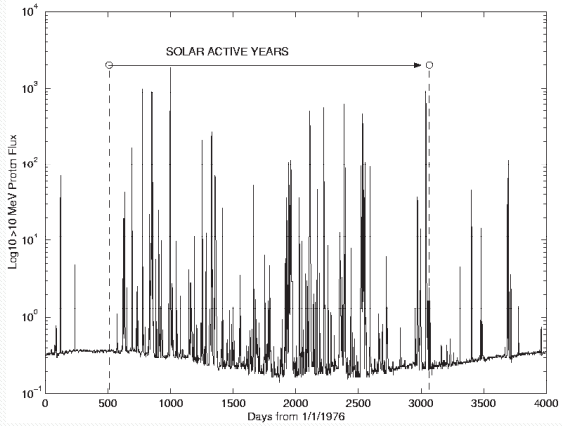
- Anomalous cosmic ray models
  - CREME96 uses data from SAMPEX and other satellites, as well as the 22-year historical record of anomalous cosmic-ray measurements; A.J. Tylka et al., IEEE Trans. Nucl. Sci., 44, 2150 (1997)
  - CREME86 model is superseded
- CREME96 proton spectrum



Interplanetary: SEPs

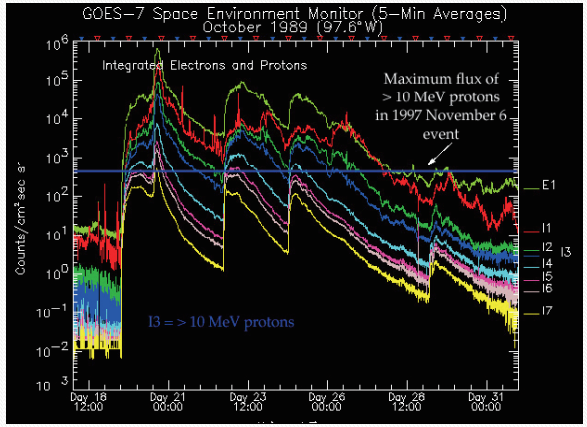
- Solar energetic particles associated with flare or CME events
- Event duration typically between several hours and several days
- Composition: protons, alpha's, heavy ions (different charge states); maybe also electrons
- Energy range: 1 MeV/nuc – 1 GeV/nuc
- Events are impossible to predict, only statistical models are available
- Magnetospheric attenuation has to be accounted for

Interplanetary: SEPs



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Interplanetary: SEPs

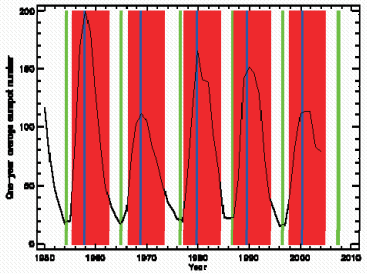


Interplanetary: SEP stat. models

- SOLPRO (J. King, *JSR, 11*, 401, 1974)
  - Based on data obtained exclusively during active years of solar cycle 20 (1966-1972)
  - Instruments on IMP-4,5,6: 10-100 MeV
  - 25 events, including Aug '72 (70% of total >10 MeV fluence for whole cycle)
  - Separation into 24 ordinary (OR) and 1 anomalously large (AL) event
  - Total predicted spectrum is sum of AL and OR spectra multiplied by number of events predicted by Burrell statistics
  - No AL events during solar minimum, but non-zero number of OR events

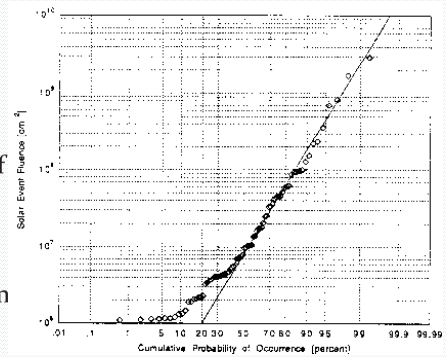
Interplanetary: SEP stat. models

- JPL (Feynman et al., *JASTP, 64*, 1679-1686, 2002)
  - Based on continuous record of daily average fluxes >1, 4, 10, 30, 60 MeV since 1956
  - Only active periods are modelled (2.5 years before and 4.5 years after solar maximum)



Interplanetary: JPL SEP model

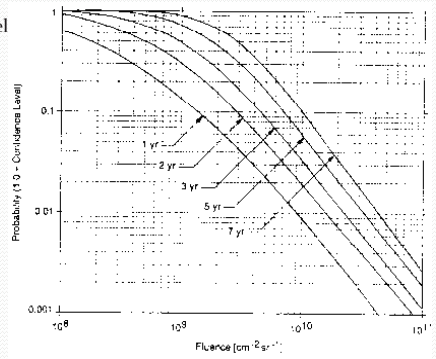
- Event fluences are assumed to follow log-normal distribution
- Poisson distribution for average number of events
- Monte Carlo simulations of random fluences from reverse lognormal distribution



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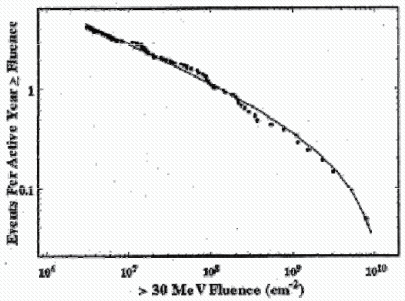
Interplanetary: JPL SEP model

- JPL model is a set of probability curves: look-up tables with interpolation between mission duration, confidence level and energy (exponential in rigidity)
- ECSS-E-10-04 standard model



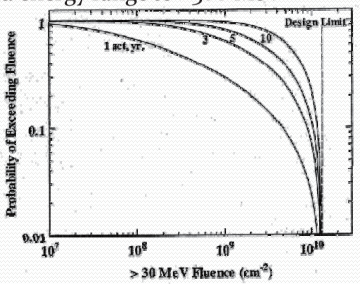
Interplanetary: ESP SEP model

- ESP: Emission of Solar Protons model (Xapsos et al.: *IEEE Trans. Nucl. Sci., 46*, 1481-1485, 1999; *47*, 486-490, 2000)
- Based on maximum entropy theory [*Kapur*, 1989]: predicts an initial distribution that is a truncated power law in the event fluence



Interplanetary: ESP SEP model

- Data from the last 3 complete solar cycles (20-22)
- Minimum fluence depends on energy
- Only solar active years are considered (cf JPL); new version (PSYCHIC) extends to solar minimum (in development)
- GOES data were used to extend energy range to >300 MeV
- Model consists of look-up tables for fluences and statistical model
- Truncated power law results in design limit: maximum expected fluence
- Two versions: total fluence or worst case event fluence

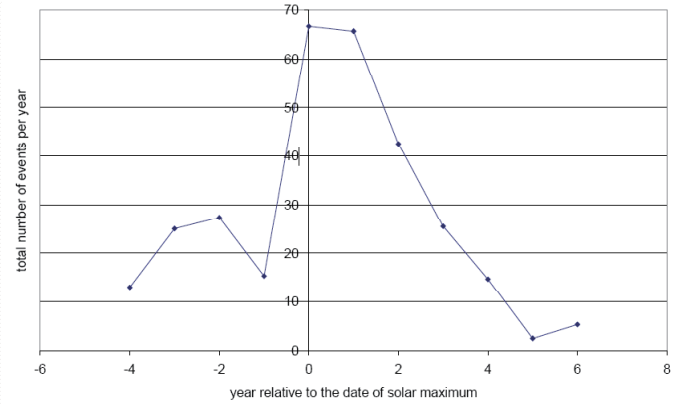


Interplanetary: SEP stat. models

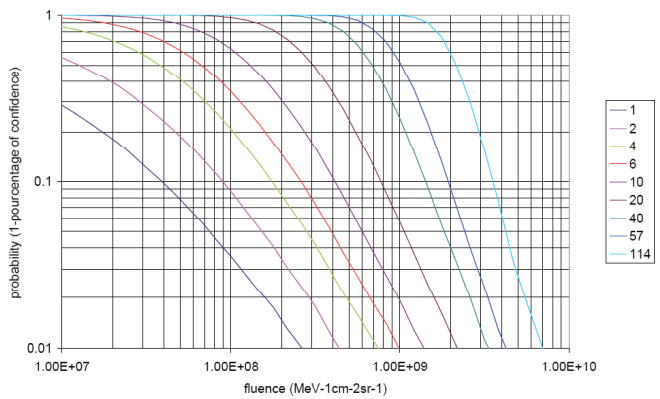
- ONERA SPOF model
  - Same methodology as JPL model: lognormal distribution
  - Data sets: GOES from 1986 to present, IMP8/CPME from 1973 on
  - Energy range: 6-300 MeV, differential fluences
  - Each year in solar cycle is related to a reference year (year 6): number of events per year relative to reference year
  - Equivalent number of years: 1 year in solar maximum = 12.5 years of reference, total solar cycle = ~57 years of reference
  - For a mission length: compute the number of equivalent years of the mission depending on the date of launch
  - Model consists of a set of probability curves

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Interplanetary: ONERA SEP model



Interplanetary: ONERA SEP model



Interplanetary: JPL "Solar Probe"

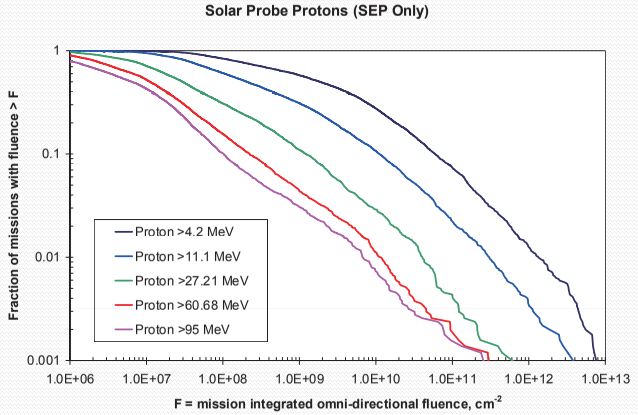
- To develop a "modular" code that estimates the mission-integrated fluences and peak fluxes for high energy protons and heavier ions with data set that covers the past 40 years of observation.
  - Arbitrary trajectory
  - Launch on an arbitrary future day
  - Statistics of SEP event fluences, durations, and intervals
  - Improved radial dependence
- To extend the "Solar Probe" Approach to long missions
- The current models were developed for missions at 1 AU for durations longer than or equal to 1 year.

Interplanetary: JPL "Solar Probe"

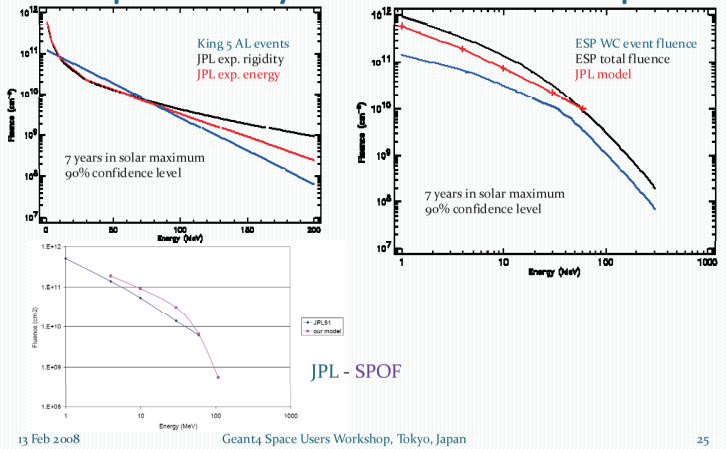
- Code to estimate mission fluences based on a method suggested for the Solar Probe mission (nearing completion?)
  - IMP-8/GSFC and IMP-8/UChicago data over the last three solar cycles
  - Fly a spacecraft through the database with an appropriate radial dependence law being applied at each time step at the beginning of a particular day.
  - Obtain the total fluence accumulated over the mission duration.
  - Repeat this process for a launch at the beginning of "each" day.
  - Calculate the probability of obtaining a fluence greater than F with a random launch date (given by the percentage of missions in which the fluence we calculated exceeded F).

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Interplanetary: JPL "Solar Probe"



Interplanetary: SEP model comp.

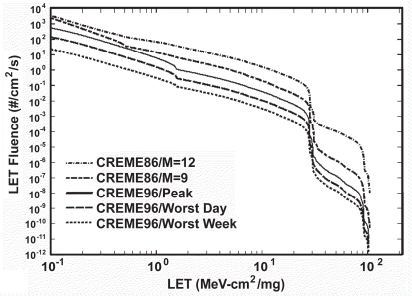


Interplanetary: SEP ion models

- CREME96
  - Worst-Week Model: based on SEP fluxes averaged over 180 hrs (7.5 days) from 1300 UT on 19 Oct 1989. *This week was the most severe SEP environment observed in the last two solar maxima and thus is a "99% worst case" environment.*
  - Worst-Day Model: based on SEP fluxes averaged over 18 hrs from 1300 UT on 20 Oct 1989 (single largest flux enhancement in Oct 1989)
  - Peak Flux Model: based on the peak five-minute averaged fluxes observed on GOES in Oct 1989

Interplanetary: CREME96 SEPs

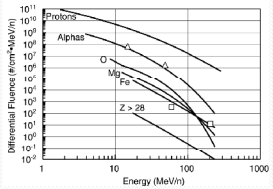
- Covers full ion range
- Takes into account charge states
- Energies up to 800 MeV/nuc
- But: based on only one event
- Fluxes can be downloaded from CREME96 site



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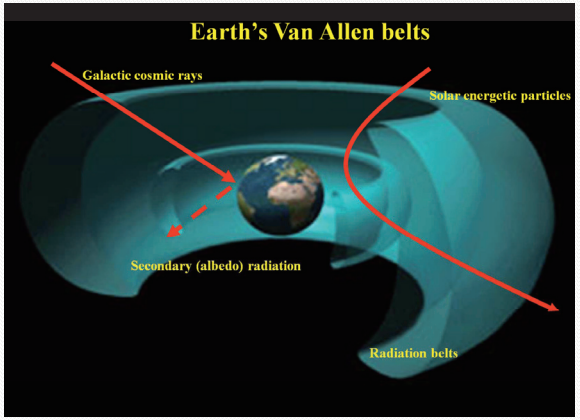
Interplanetary: SEP ion models

- Extension of the PSYCHIC model to ions (Xapsos et al., IEEE NSREC07, B-4)
  - Nearly all naturally occurring elements in the periodic table
  - Energy coverage up to 300 MeV/nuc
  - Only valid for solar maximum years



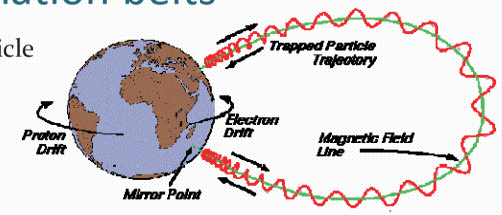
2-year mission during solar maximum at the 90% confidence level

Earth radiation belts

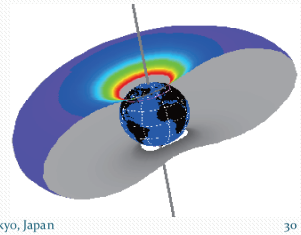


Earth radiation belts

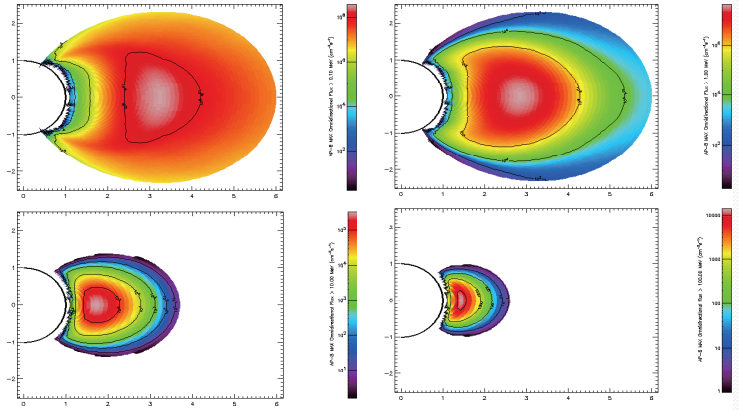
Charged particle trapping



- Particle motion: gyration, bounce, drift
- Guiding centre approximation: McIlwain's (*B*,*L*) coordinates
- Model description: *J*(*E*,*B*,*L*)

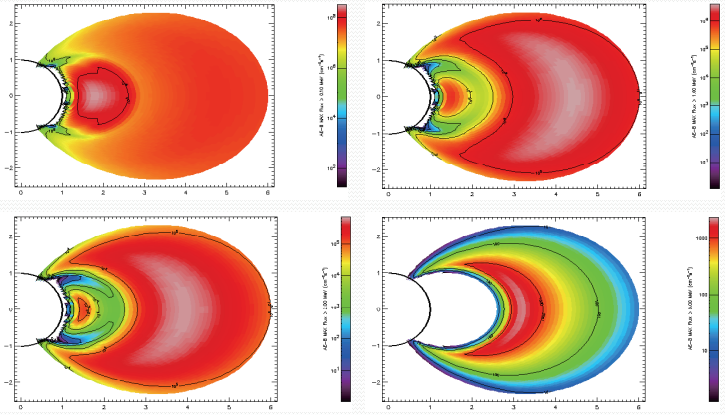


Earth radiation belts: Trapped p+



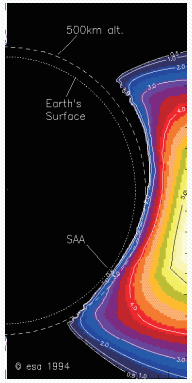
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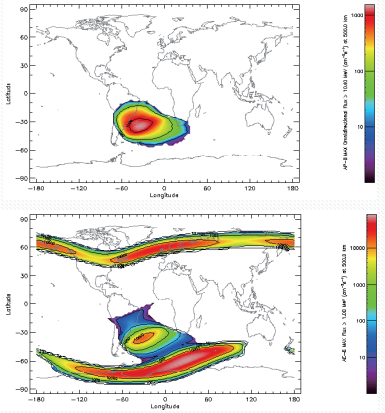
Earth radiation belts: Trapped e-



Earth radiation belts: SAA

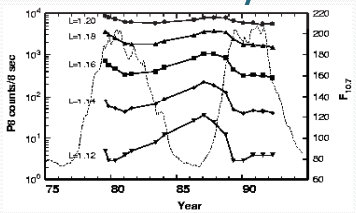
South Atlantic Anomaly

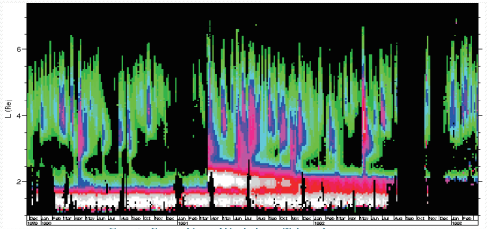




Earth radiation belts: Variability

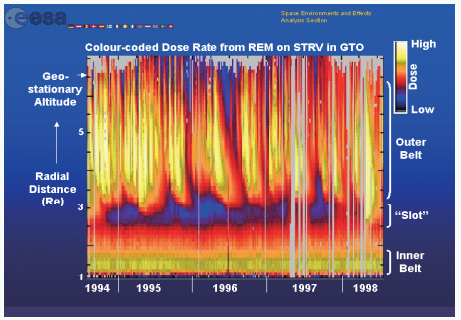
- Trapped proton variability
  - Solar cycle
  - Seasonal
  - Secular variation of geomagnetic field
  - Impulsive





Earth radiation belts: Variability

- Trapped electron variability
  - Solar cycle
  - 27 day solar rotation period
  - Impulsive



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Earth radiation belts: AP-8, AE-8

- De facto standard models (ECSS-E-10-04), although built in 1960's
- Two versions of each, MIN and MAX, for solar minimum and maximum conditions
- Lookup tables with interpolation routines (improved version made by ESA/ESTEC)
- Available from NSSDC: http://nssdc.gsfc.nasa.gov/space/model/magnetos/aeap.html

Model	Energy range (MeV)	Coordinate range (L)	Reference
AP-8	0.1-400	1.14 – 6.6	Sawyer, D. M. and J. I. Vette, *NSSDC/WDC-A-R&S 76-06*, 1976
AE-8	0.04-7	1.14 – 12	Vette, J. I., *NSSDC/WDC-A-R&S 91-24*, 1991

Earth radiation belts

ORBIT	MODEL	DEVELOPER	DATA SOURCE, EPOCH	PARTICLE, ENERGY RANGE	FEATURES	AVAILABILITY
LEO: L=1.1-2.0	PSB97 (proposed standard)	BIRA/ Aerospace Corp., 1997 [17]	SAMPEX-PET 1995	Directional, differential/ integral protons 18.5 – 500 MeV	Valid for solar minimum Internal field model	SPENVIS
LEO: 250-850 km LEO, MEO: 300 km-<GEO	LATRM (formerly NOAAPRO) TPM-1 (proposed standard)	The Boeing Co., 1998 [18] S.L. Huston The Boeing Co., 2002 [19]	TIROS/NOAA 11/78-10/95 (6 satellites) TIROS/NOAA 11/78-10/95 CRRES-PROTEL 7/90-10/91	Omnidirectional, integral protons >16, >30, >80 MeV Omnidirectional, differential protons 1.5 – 81.3 MeV	True solar-cycle variation using $F_{10.7}$ proxy for driver Internal field model Secular var. of B_{ijm} Low-alt. solar-cycle variation using $F_{10.7}$ proxy for driver Internal field model Secular var. of B_{ijm} 1 month time resolution Quiet/Active models	NASA/MSFC-SEE Program NASA/MSFC-SEE Program
MEO: L=1.4-5.5	CRRESPRO	AFRL, 1993 [20]	CRRES-PROTEL 7/90-10/91	Omnidirectional, differential/integral protons 1 – 100 MeV	Valid for solar maximum Quiet/Active models Internal & external field models	AFRL/VSBXR, SPENVIS
MEO, GEO: L=2.4-6.8	CRRESELE	AFRL, 1992 [21]	CRRES-HEEF 7/90-10/91	Omnidirectional, differential/integral electrons 0.5 – 6.6 MeV	Valid for solar maximum Driven by Ap_{15} Internal & external field models 6 Ap15-dependent models, plus average & worst-case models Outer electron belt only	AFRL/VSBXR, SPENVIS
MEO, GEO: L=3-8	FLUMIC	DERA, 1999 [22]	GOES-7-EPM 1987-1998 LANL GEO ESP 9/89-10/98 STRV-1b REM 8/94-5/98	Directional, integral electrons > 0.2 to > 5.9 MeV (20 increments)	Worst-case 1-day fluence Code adjustable to reflect worst cases due to SPEs/CMEs Solar-cycle variation Internal & external field models Created for DICTAT, an internal charging model	SPENVIS, QinetiQ
GEO	POLE (proposed standard)	LANL/ONERA, 2003 [23]	LANL GEO CPA/SOPA 1976-2001 (13 satellites)	Omnidirectional, differential/integral electrons 0.03 – 2.5 MeV	Mean, worst- and best-case models Solar-cycle variation (data from 2.5 cycles) 1 year time resolution	ONERA/DESP, TRAD: OMERE

Lauenstein & Barth, Radiation Effects Data Workshop 2005, IEEE

Earth radiation belts: Other models

- Combination of satellite data and numerical code Salammbô (developed and run by ONERA/DESP): ESA study RERMM (Radiation Environment Research from Multiple Monitors)
- On the fly from satellite data, e.g. SEES (Space Environment Effects System): http://sees.tksc.jaxa.jp
- Next Generation Radiation Specifications Consortium (NGRSC)
  - Consortium to build AP-9/AE-9
  - Contacts:
    - Dr. G.P. Ginet, AFRL, gregory.ginet@hanscom.af.mil
    - Dr. T.P. O'Brien, Aerospace Corp., paul.obrien@aero.org
    - http://lws-set.gsfc.nasa.gov/RadSpecsForum.htm

Other planets

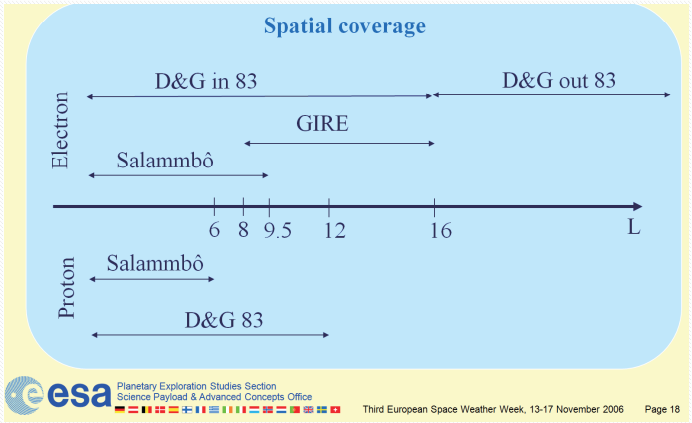
- Jupiter radiation belts: very high energy electrons and protons
- Saturn probably has radiation belts, but no models
- Interplanetary radiation field at other planets:
  - Helioradial distance scaling
    - Still very controversial for SEPs: R^{-2}, R^{-3}, other?
    - Part of the ESA SEPEM (Solar Energetic Particle Environment Modelling) study: http://www.oma.be/SEPEM/
    - Probably not an issue for cosmic rays
  - Interaction with planetary magnetic fields and atmosphere (PLANETOCOSMICS)

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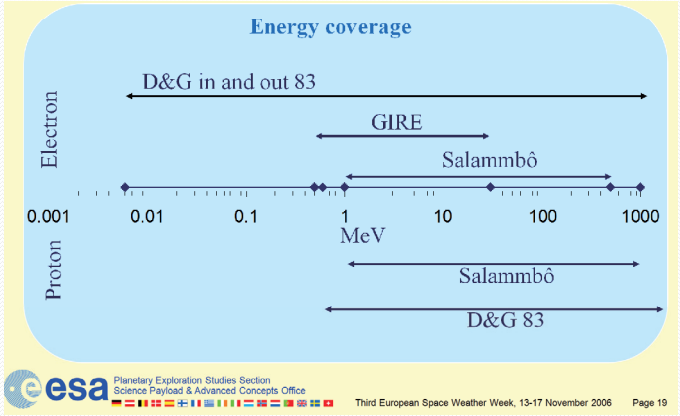
Other planets: Jupiter belts

- Divine & Garrett model (*JGR*, 88, 6889-6903, 1983) from JPL
  - Empirical model based on Pioneer and Voyager measurements, obervations from Earth and theory
  - Good coverage in space and energy
  - But based on old data set (outdated pitch angle model and magnetic field model)
- GIRE (Galileo Interim Radiation Electron) from JPL (Garrett et al., *GRL*, 32, 2005)
  - Update of Divine & Garrett with Galileo data
  - Only electrons between 8-16 R_J
  - Available from http://www.openchannelfoundation.org/projects/GIRE/
- Salammbô-3D (Sicard and Bourdarie, *JGR*, 109, 2004) from ONERA
  - Physical model derived from Salammbô-3D
  - Global model limited to 6-9 R_J

Other planets: Jupiter belts



Other planets: Jupiter belts



Geant4 tools in SPENVIS

- Integrated user environment: automatic generation and ingestion of spectra; http://www.spenvis.oma.be/
- Currently available: Mulassis, GEMAT, SSAT, sectoring tool (GDML output for SSAT)
- Under development: NIEL based tool for solar cell damage, PLANETOCOSMICS, MarsREM radiation effects models
- Fortran pre-processor converts spectra into gps macro's
- Demo using GEMAT

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Geant4 implementation issues

- Geant4 is a very complex set of libraries and tools
- Versioning issues with GDML etc.
  - Example: new definition of micrometer in macro's
  - Problems with building applications on Windows: complex for XP, impossible for now with Vista!
  - Versions of radiation data
- Static builds of stand-alone applications are the only viable distribution for non-expert users! Even then, macro's can differ from one version to the next… (um)!
- Distribution of radiation data: ten thousand files, very cumbersome for operating system!
- Improvement of EPS and VRML output (add viewpoints)

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