Space environment and effects analysis for ESA missions

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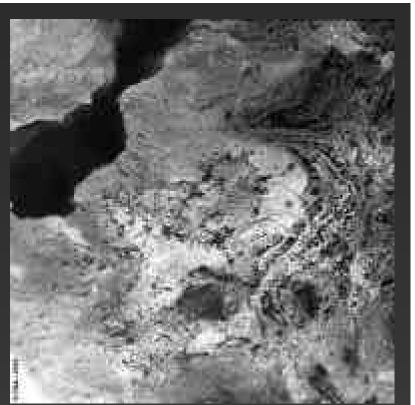
ESA / ESTEC

** RHEA Ltd*

9th Topical Seminar on Innovative Particle and Radiation Detectors
23 - 26 May 2004   Siena, Italy

The European Space Agency

- ESA is an intergovernmental organisation with a mission to provide and promote, for exclusively peaceful purposes:
  - space science, research and technology
  - space applications
- About 90% of ESA's budget is spent on contracts with European industry, mainly for research and development
- ESA purpose is to:
  - Improve competitiveness of European industry
  - Conduct cost-effective research and development, and operations
- http://www.esa.int


The European Space Agency:
Members and Programmes

- 15 member states
  - Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Norway, The Netherlands, Portugal, Spain, Sweden, Switzerland and the United Kingdom
  - Greece and Luxembourg are expected to become members of ESA in 2004
- Cooperation agreements with Canada and Hungary

- ESA / EU Framework Agreement
  - The two organisations share a joint European strategy for space and together are developing a European space policy.

- Budget
  - Mandatory and optional activities
  - €2700 million in 2003 invested on the basis of geographical return

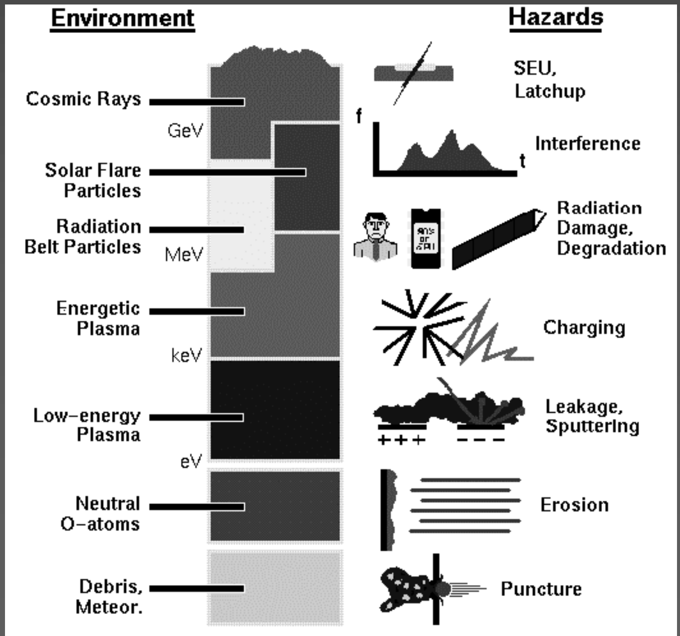
- ESA programmes:
  - Earth observation
  - Micro gravity research
  - Telecommunications
  - Launcher development
  - Navigation
  - Manned space flight

ESTEC
European Space Research and Technology Centre

- ESA sites:
  - HQ, ESOC, EAC, ESRIN, ESTEC
- ESTEC (Noordwijk, The Netherlands)
  - ESA's largest establishment (~1000 staff)
  - Principal functions:
    - project management
    - future studies
    - space science
    - conception & management of ESA's space technology programme
    - provision of technical expertise and laboratory facilities
    - spacecraft testing
- http://www.estec.esa.int

ESA Space Environments and Effects section – TEC-EES

- Provides technical support to ESA programmes in the area of space environments and effects
  - Meteoroids and space debris
  - Atmosphere modelling
  - Radiation in space
  - Space weather
  - Spacecraft plasma interactions

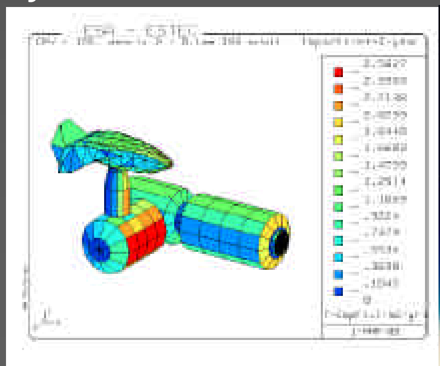


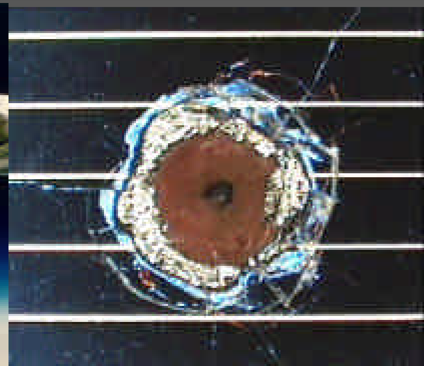
- Project support
  - Before mission
    - Space Env. Specifications
    - Long term forecast
  - During mission
    - Specs. Update
    - Special actions
  - During or Post mission
    - Past space env. determination for detailed analysis

Meteoroids and Space Debris

- Man-made space debris and natural micrometeoroid particles
  - can damage satellites and
  - constitute a serious hazard to manned space flight
- Evaluating space debris and micrometeoroid size and velocity
  - analyzing their effects
  - designing efficient shielding

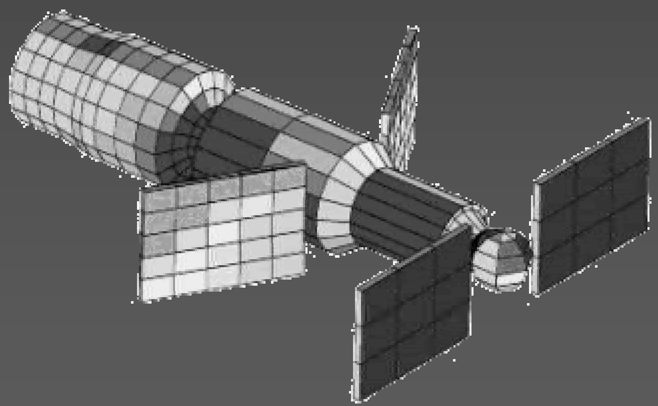
- Main areas covered:
  - Impact risk assessment
  - *In-situ* detectors
  - Analysis of retrieved hardware





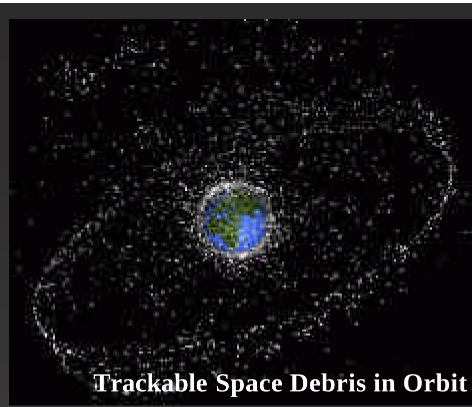
Meteoroids/Space Debris
Mission support

- Specification of fluxes for given mission
- Simplified analysis
  - Fluxes only
  - Random plate
  - Damage assessment for fixed impact direction and velocity using simple damage equation
- Full 3-D analysis using ESABASE/DEBRIS



- Ex: Development of damage equations for ATV
  - HVI test, 4 mm Alu sphere, 7.2 km/s @ 45 deg. bumper=1.2 mm, backwall=3.3 mm, S=49.5 mm

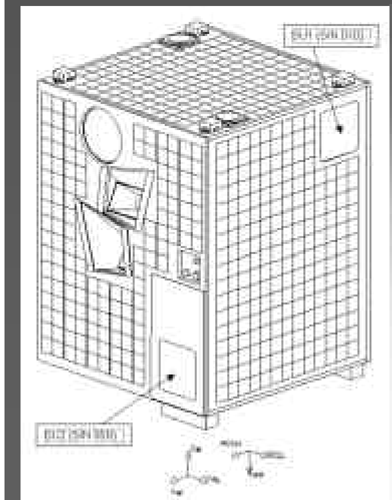
Meteoroids/Space Debris
In-Orbit Data

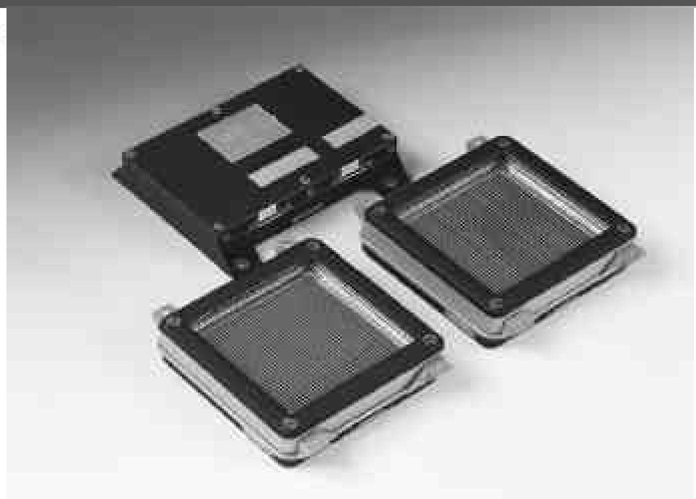


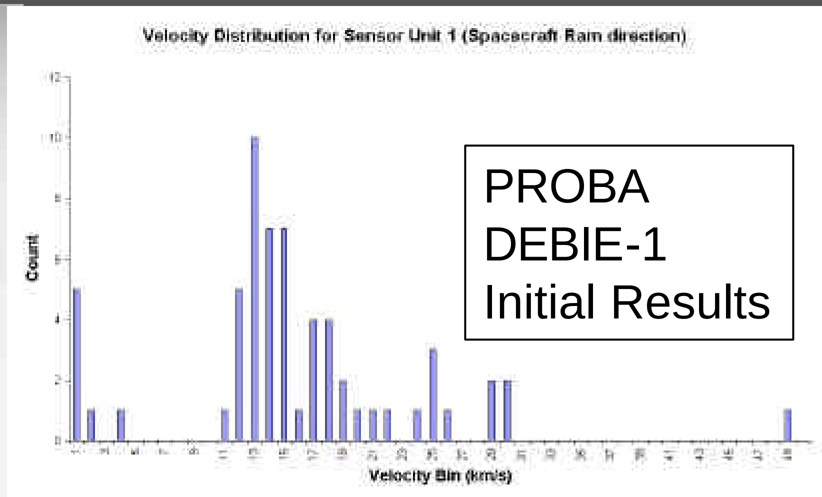
- Space debris is tracked by radar down to about 10 cm in LEO and 1 m in GEO
- Dedicated radar or optical measurements can go down to 0.5 – 1 cm in LEO and 15 – 20 cm in GEO

- Information on smaller particles (which are the most abundant by far) can only be obtained by:
  - *In-situ* detectors (ESA: GORID in GEO, DEBIE in LEO
  - Analysis of retrieved hardware (ESA: Eureca, HST solar arrays)

- DEBris In orbit Evaluator (DEBIE)
  - 2 Sensor Units (opening 10cm x 10 cm)



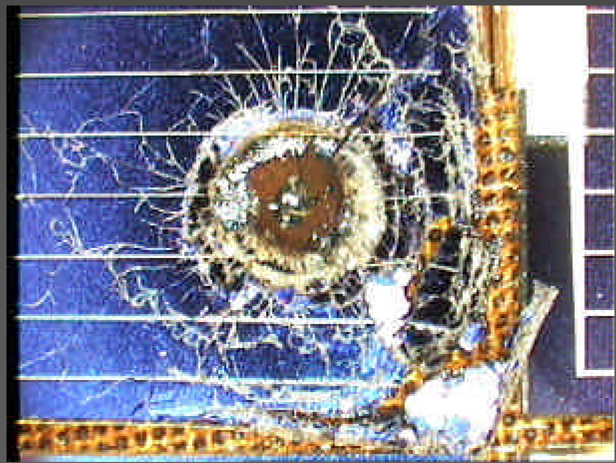




Meteoroids/Space Debris
retrieved hardware

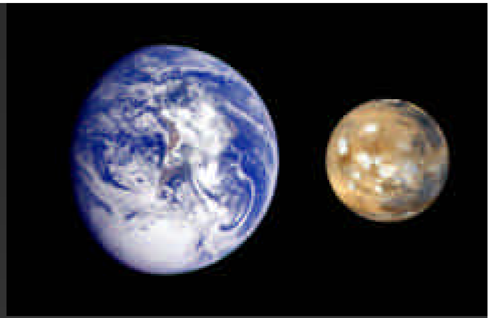
- HST Post-Flight Impact studies
  - Global survey of all surfaces for impact features.
  - Photographic recording of all craters larger than 3.7 mm
  - Recording of smaller craters (down to microns sizes) for selected areas.
  - Chemical analysis of crater residues to distinguish meteoroids from debris.
  - Data analysis and establishment of database
  - Validation of flux models.

HST Solar Array
Stiffener Material
Feature size: 2 mm



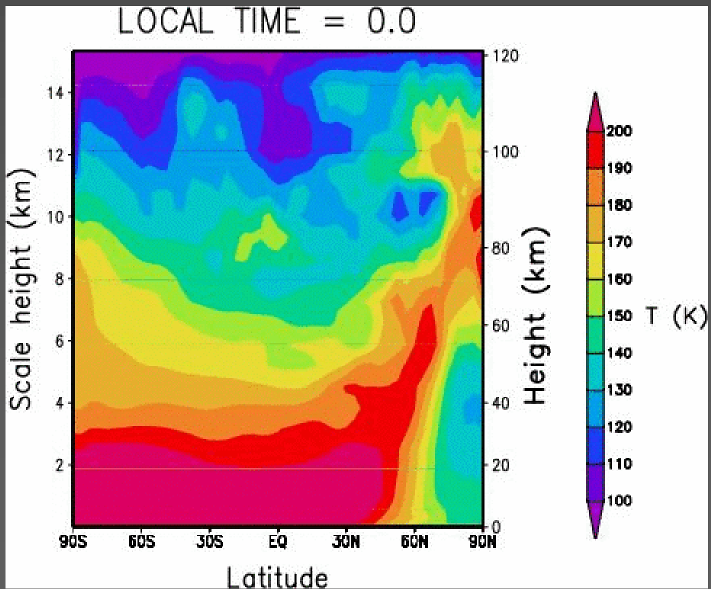
HST Solar Cell
Impact from front side
Crater size: 3.5 mm
Hole size: 0.8 mm

Atmosphere(s) modeling

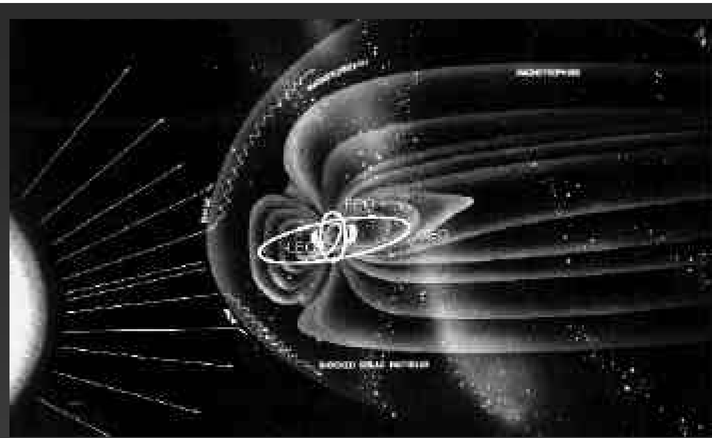


- Global Circulation Models (GCM) for moons and planets (Earth, Mars, …)
- Ground and atmospheric environments and effects on detectors (e.g., scattering coefficients).

- Model based Martian Climate Database
  - Continuously improved
  - http://www-mars.lmd.jussieu.fr/

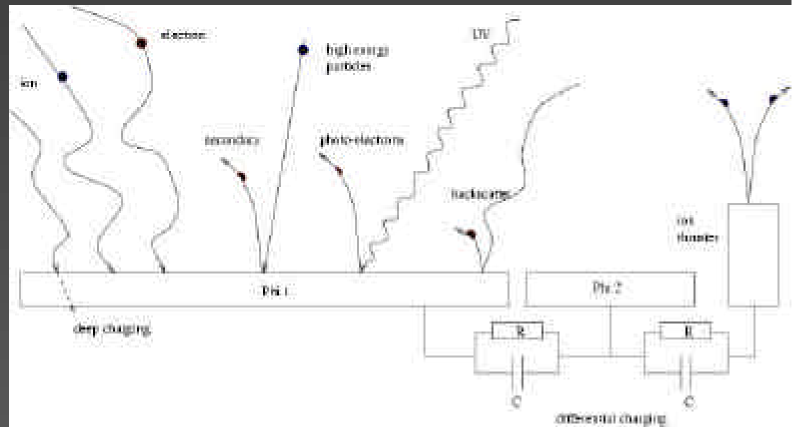


Spacecraft plasma interactions



- Plasma environments
  - At high altitudes and in polar orbits result in electrostatic charging of spacecraft surfaces
  - At low altitude cause leakage of power from exposed solar arrays and electromagnetic perturbations

  - Disturbance of scientific measurements
  - Surface damage or electronic disturbance
  - Shortcut of high voltage system
  - Plasma perturbations affecting wave propagation

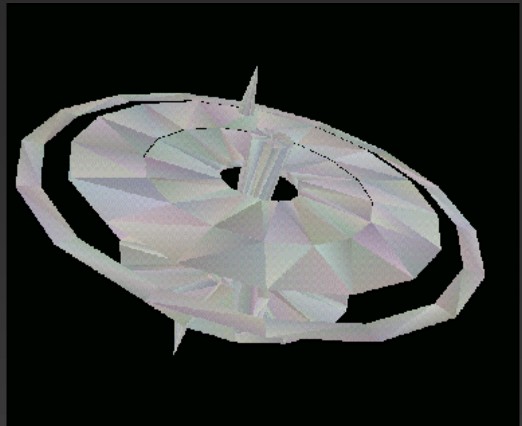


$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_0 e^2}}$$

Orbit	Altitude	Temperature	Density	λ_D
LEO	± 300 km	0.1 eV	$n_e \sim 10^6$ cm^{-3}	$\lambda_D \sim 1$ mm
PEO	± 800 km	1 eV	$n_e \sim 10^4$ cm^{-3}	$\lambda_D \sim 1$ m
GEO	± 36000 km	5 to 20 keV	$n_e < 1$ cm^{-3}	$\lambda_D \sim 100$ m

Plasma modeling
PicUp3D

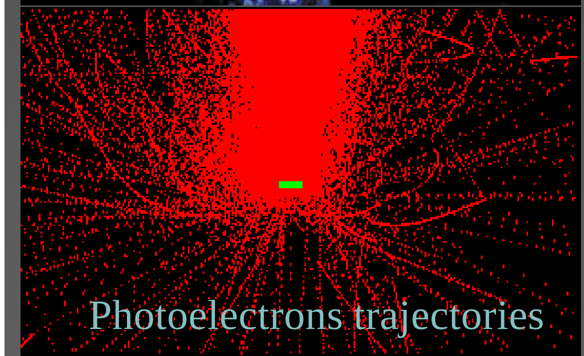
- ESA open source approach
  - Need of a simulation software to model complex spacecraft/plasma interactions
  - Most advanced codes are not available for the European spacecraft charging community:
    - NASCAP-2K is export restricted
    - Most of the codes are in-house proprietary software
  - Open source approach allows
    - Low cost, community based development
    - High possibilities of extensions and adaptation to particular studies requirements
    - Education applications

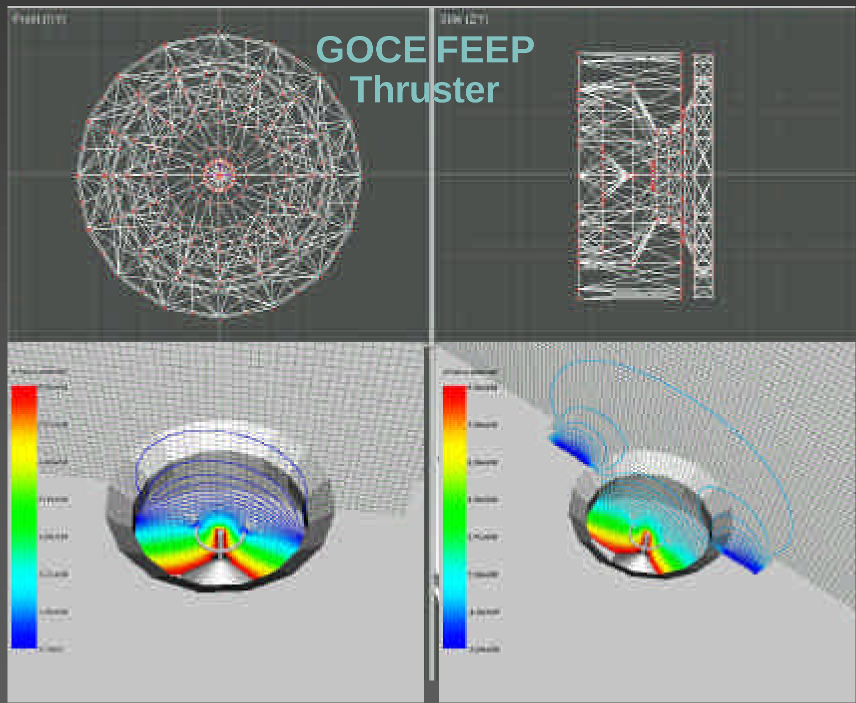


Freja model

- PicUp3D simulation code prototype
  - Developed in the frame of the SPINE Network by a PhD student
  - Open source
  - 3D Particle-In-Cell approach.
  - Implemented in JAVA.
  - Vlasov-Poisson problem approximated by the motion of macro-particles interacting with self-consistent E and imposed B.
  - Triangular unstructured mesh to describe a detailed spacecraft geometry
  - Now fully operational, validated and used for mission support

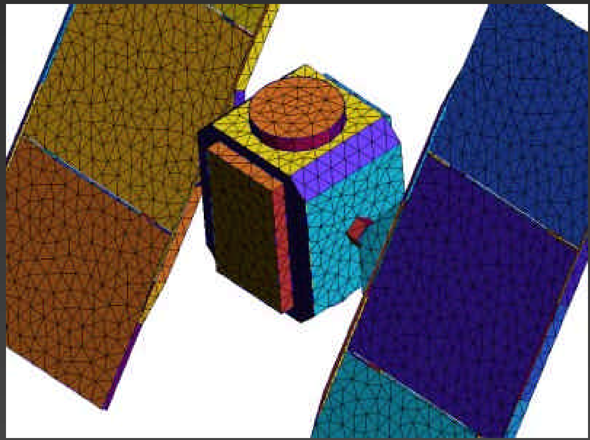
S/C Plasma interaction
Mission support with PicUp3D





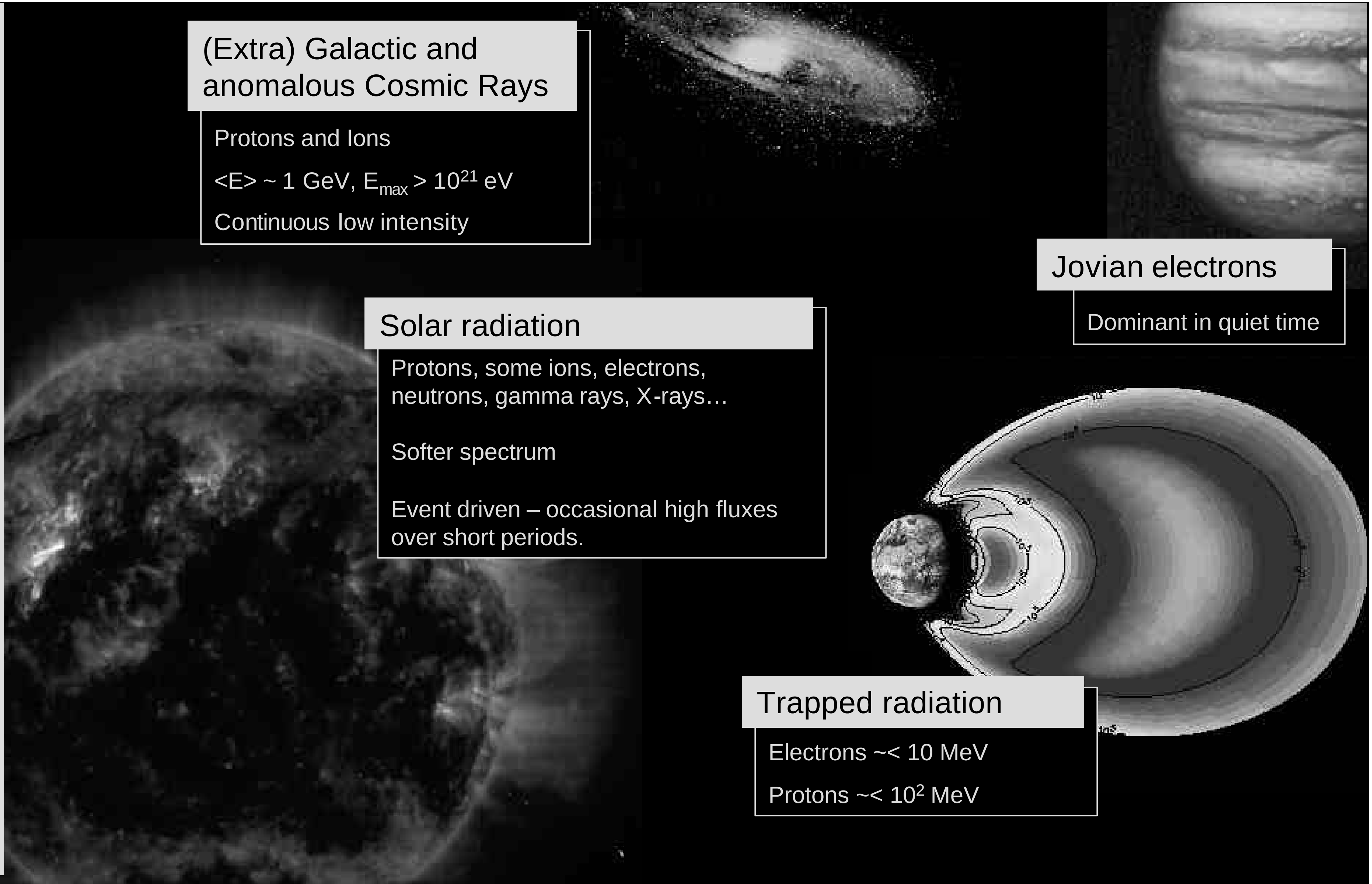
Plasma modeling
SPINE / SPIS

- SPINE Community
  - Spacecraft Plasma Interaction Network in Europe
  - Objective: coordinating efforts in all domains related to spacecraft charging and sharing resources
  - Numerical analysis methods and algorithms, software architecture and data interface (code implementation, validation techniques, testing and post-processing, common Library of generic routines for s/c-plasma-interaction simulations)
  - Development of a database on material properties, environmental data and space flight observations
  - Development of a Database of results and publications
  - Preparing in orbit investigations
  - Establishment standard procedures and method for hardware design
  - Training of young scientists and engineers
  - Establishment of External collaborations
- http://www.spis.org/spine



- SPIS
  - Community development and validation: development for the community, by the community
  - Modular and adaptable software
  - New functionalities (full 3D unstructured mesh…)
  - Web interface for information and data exchange
  - Development by ONERA, Artenum, Paris 7 under ESA contract
- http://www.spis.org/spis

Sources



(Extra) Galactic and anomalous Cosmic Rays

Protons and Ions

<E> ~ 1 GeV, $E_{max} > 10^{21}$ eV

Continuous low intensity

Jovian electrons

Dominant in quiet time

Solar radiation

Protons, some ions, electrons, neutrons, gamma rays, X-rays…

Softer spectrum

Event driven – occasional high fluxes over short periods.

Trapped radiation

Electrons ~< 10 MeV

Protons ~< 10^2 MeV

Effects

Single Event Effects

SE Upset

SE Latchup

Degradation

Ionisation, Displacement

Components, solar cells, detector parameters

Charging

Discharges

Interferences from electro-magnetic systems

Background

Spurious signals

Detector overload

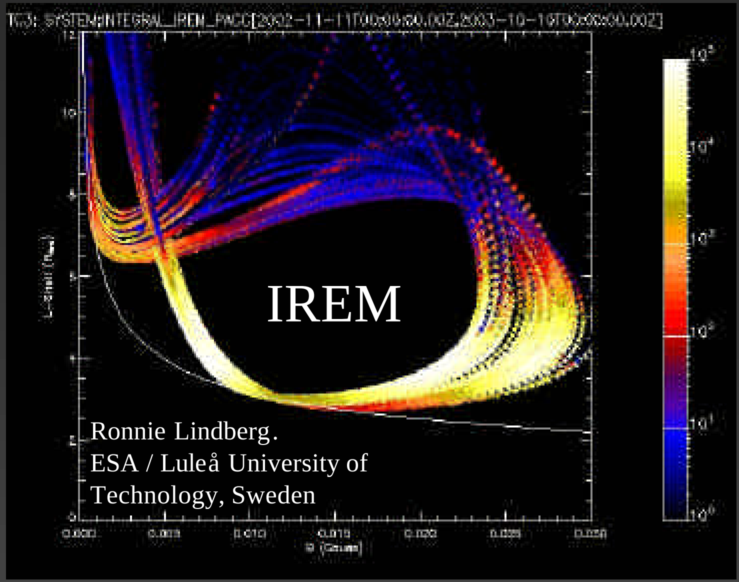
Threats to life

Dose (Equivalent dose) in manned space flights

Radiobiological effects

Radiation Monitors
(with TEC-QCA)

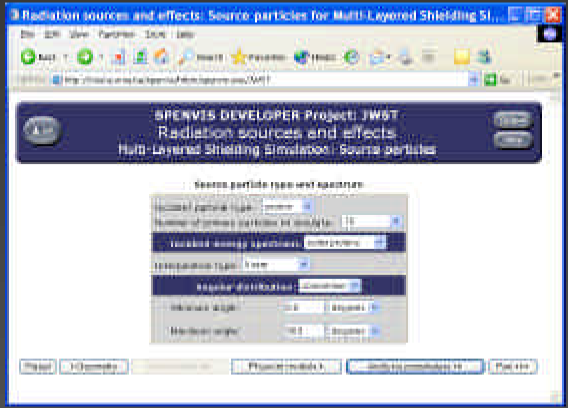
- REM [1kg, 130x100x80mm]
  - protons (>30MeV) and electrons (>1MeV)
  - STRV-1b ('94-'98), MIR ('94, '96)
- SREM [2.5kg, 96 mm x 122 mm x 217 mm]
  - electron flux (0.3-6 MeV), proton flux (8-300 MeV) total radiation dose
  - STRV-1c, Proba (Oct, '01), Integral (Oct, '02), Rosetta (Feb, '04)
  - Future - GSTB V2 ('05), Herschel ('07), Planck ('07), Gaia (~'10)
- MRM [<200g, 64x42x20mm]
  - Based on simple scintillator design
  - Proba ('01)
  - 2 new flight models expected in '06
- Future…



SEDAT, SPENVIS

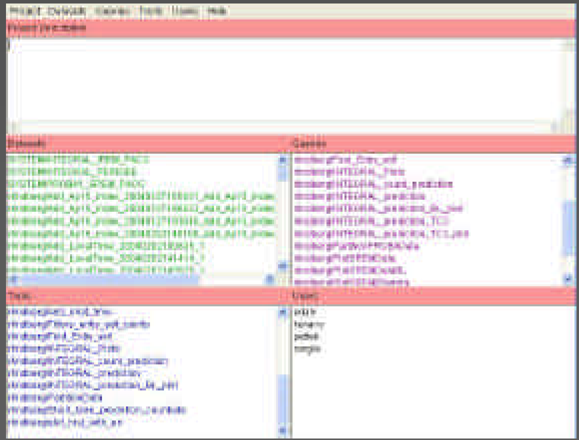
- SPENVIS – Space Environment Information System
  - Comprehensive implementation of space environment and effects models and tools
  - Frequent downloads of data from online sources e.g. NOAA
  - New models can be integrated into the system

  - http://www.spenvis.oma.be/spenvis



- SEDAT – Space Environment Data System
  - Database of space missions and monitors
  - Simplified, programmable access to data and meta-data
  - Support for inclusion of additional user-defined datasets
  - Users can collaborate and share datasets

  - http://www.wdc.rl.ac.uk/sedat

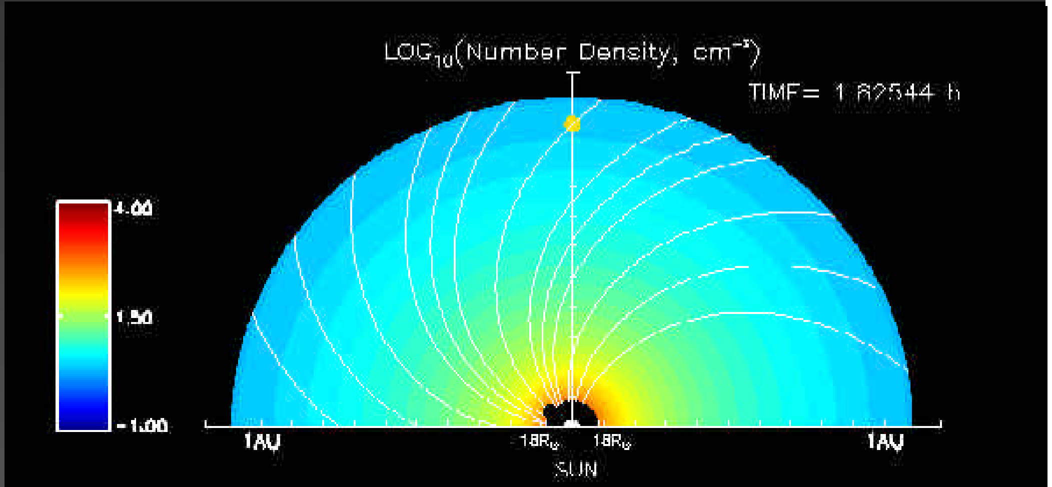


Radiation Environment
Model Development

- TREND: Trapped Radiation Model Developments (1989-'99)
  - Methods to improve static models constructed from 1960s data
    - radiation belt dynamics
    - correlation with geophysical parameters.
  - use of new data sets and advances in radiation belt physical simulations
  - inner proton belt interactions with the atmosphere
  - Update of UNIRAD – radiation environment software package and development of UNILIB - subroutine library for software development.
  - http://www.magnet.oma.be/home/trend/trend.html

- RERMM: Radiation Environment Research from Multiple Monitors
  - Develop tool to interpolate between heterogeneous measurements of ionising particles
  - Future anomaly analysis and characterisation of detector background

- Possible Interpolation and/or Forecast Tool for SPEs
  - Simulation of shock propagation to 1 AU



Produced by Angels Aran and Blai Sanahuja of University of Barcelona and David Lario of Johns Hopkins University

- Energetic Electron Environment Models for MEO
  - Galileo system interaction with the outer electron belt
  - Open competition

Particle transport simulations in the space environment domain

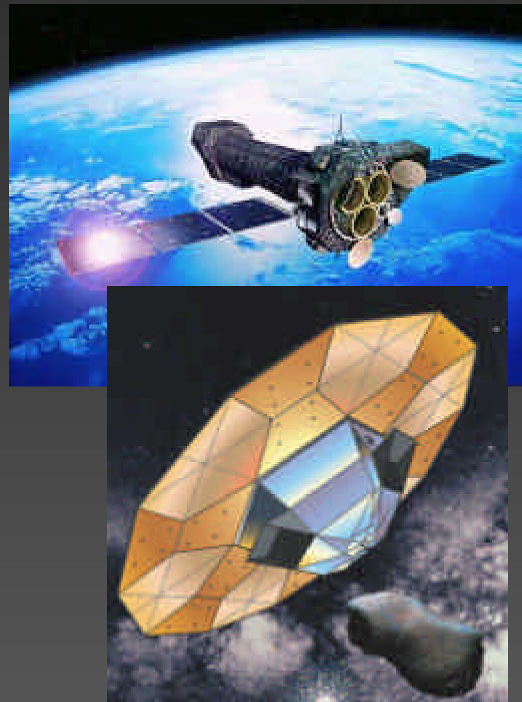
- Interaction of environment particles with spacecraft structure and detectors
  - Primaries, secondary particle production
  - Dose estimation (Ionising, Non-Ionising)
- Microscopic effects description
  - Charge balance, SEE, displacement damage,…
- Space environment modeling
  - Trapped radiation (Earth, Mercury,…)
  - Atmospheric showers (Earth, Mars,…)
- Scientific detector studies (signal extraction, background estimation,…)

- Result uncertainties
  - Simulation engine models
  - Component parameterisation
  - Geometry model approximations
  - Systematics from the space environment models
- ESA is trying to address all these aspects
  - In-house work
  - External contracts

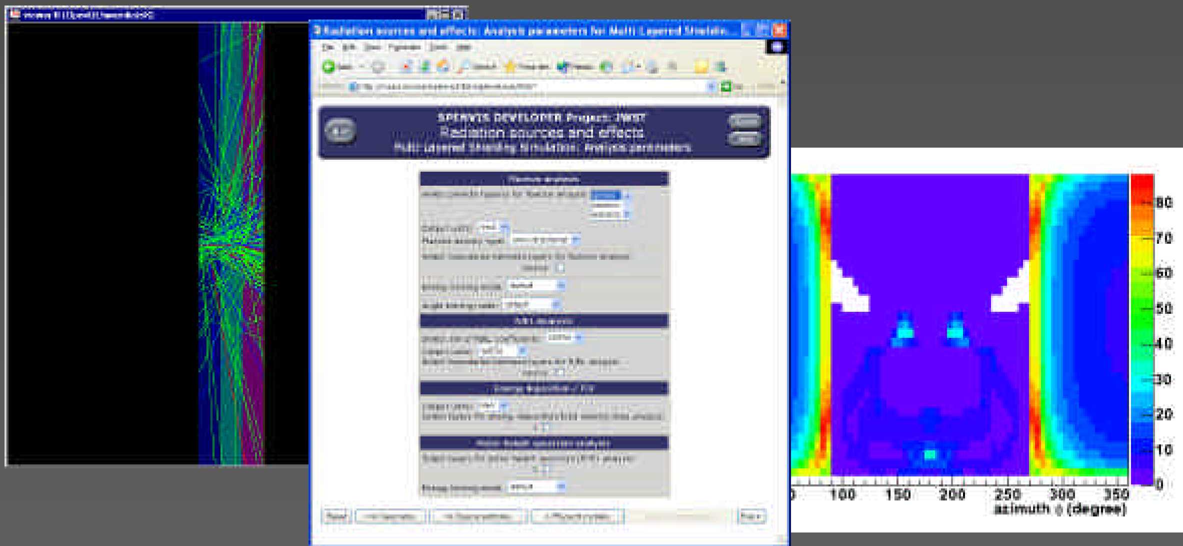
- MC tool requirements
  - Physics description → proton, electron, ion, neutron, pion, gamma (+X-ray), optical photons
  - Wide energy range
  - Geometry description (I/O, flexibility)
- Geant4 chosen by ESA as standard simulation toolkit for particle transport
  - Becoming adequate for the description of the relevant phenomena

Mission simulation and engineering tools

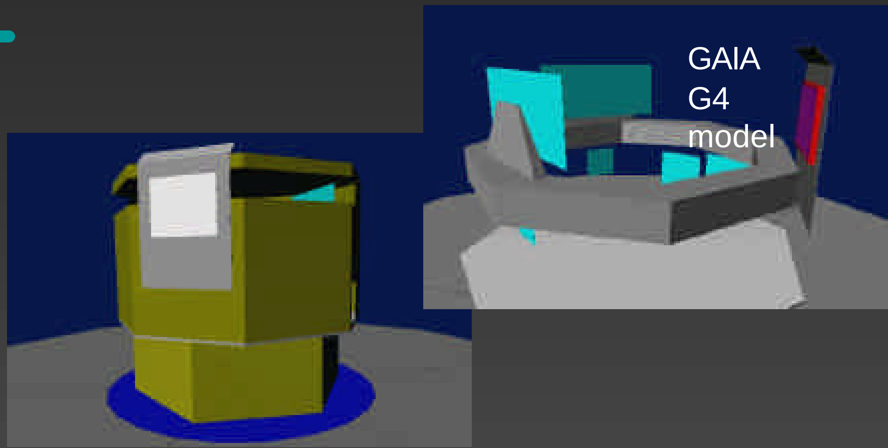
- “Applications” targeted at a specific mission or problem
  - Mission analyses
    - Degradation, background, charging
    - Examples: XMM, GAIA, Smart-2
  - Radiation monitors: design and calibration
    - SREM, MRM

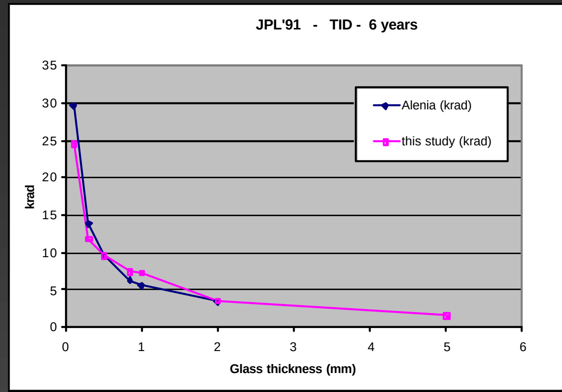


- Simulation “engineering tool” development
  - Shielding optimization
  - Radiation effects to detectors/components
  - SSAT, MULASSIS, NIEL

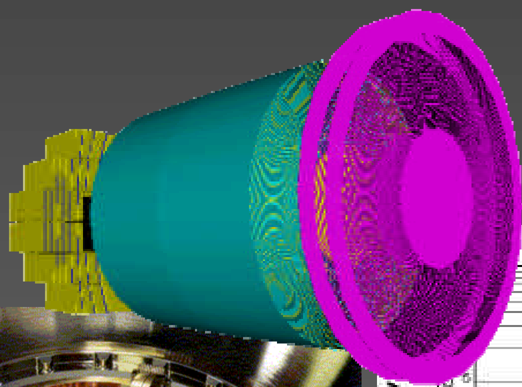


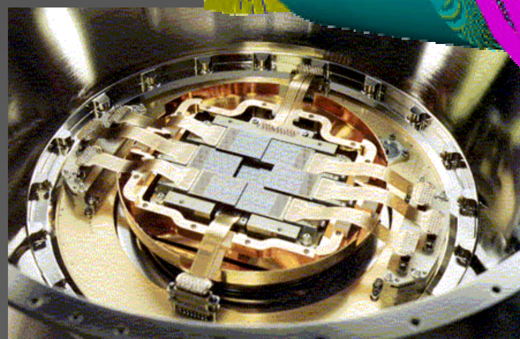
Geant4
Mission specific support

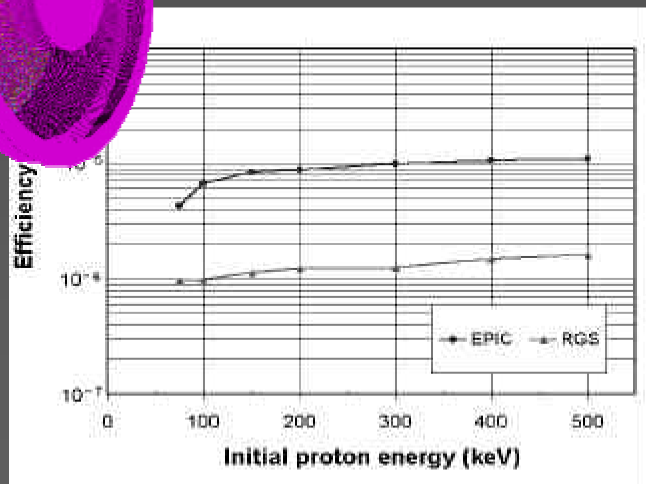




- GAIA
  - 2011, L2 orbit
  - Focal plane CCD
  - High fluence, TID, NIEL
  - Waiting for new shielding design

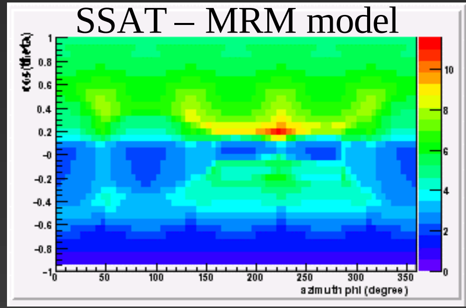




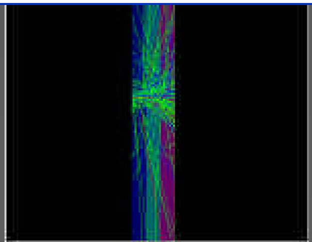


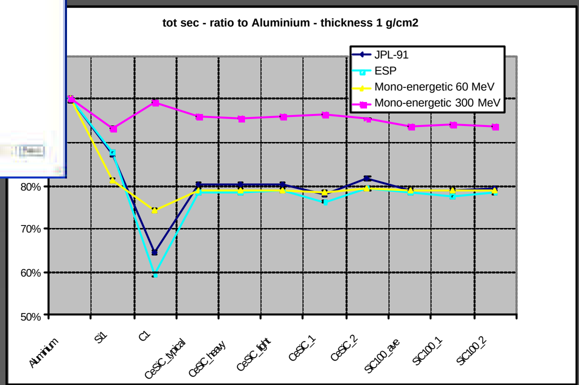
- XMM / NEWTON
  - Radiation belt passages
  - FP detector
  - Grazing angle proton scattering
  - Instrument shielded during high fluxes

Geant4-based engineering tool development



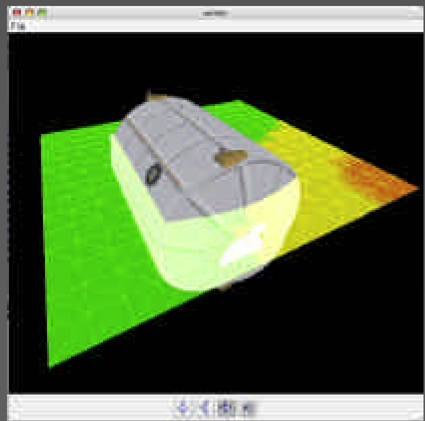
- MULASSIS
  - MUlti-LAyer Shielding Simulation Software
  - Geant4 based, for shielding calculations
  - Integrated into SPENVIS with a WWW interface
  - Source code and precompiled executables downloadable
  - Shielding assessment, Solar array, …





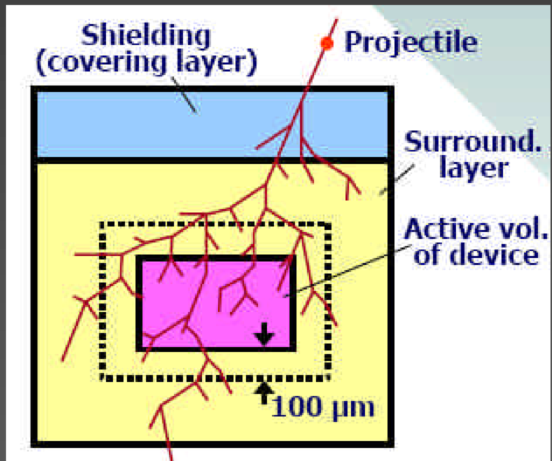
- SSAT
  - Sector Shielding Analysis Tool
  - Ray tracing: shielding levels and shielding distribution from a user-defined point within a Geant4 geometry

- DESIRE RadVis
  - 3D visualization of radiation flux and dose levels in and around the module
  - improve radiation awareness of astronauts and ground personnel at ESA



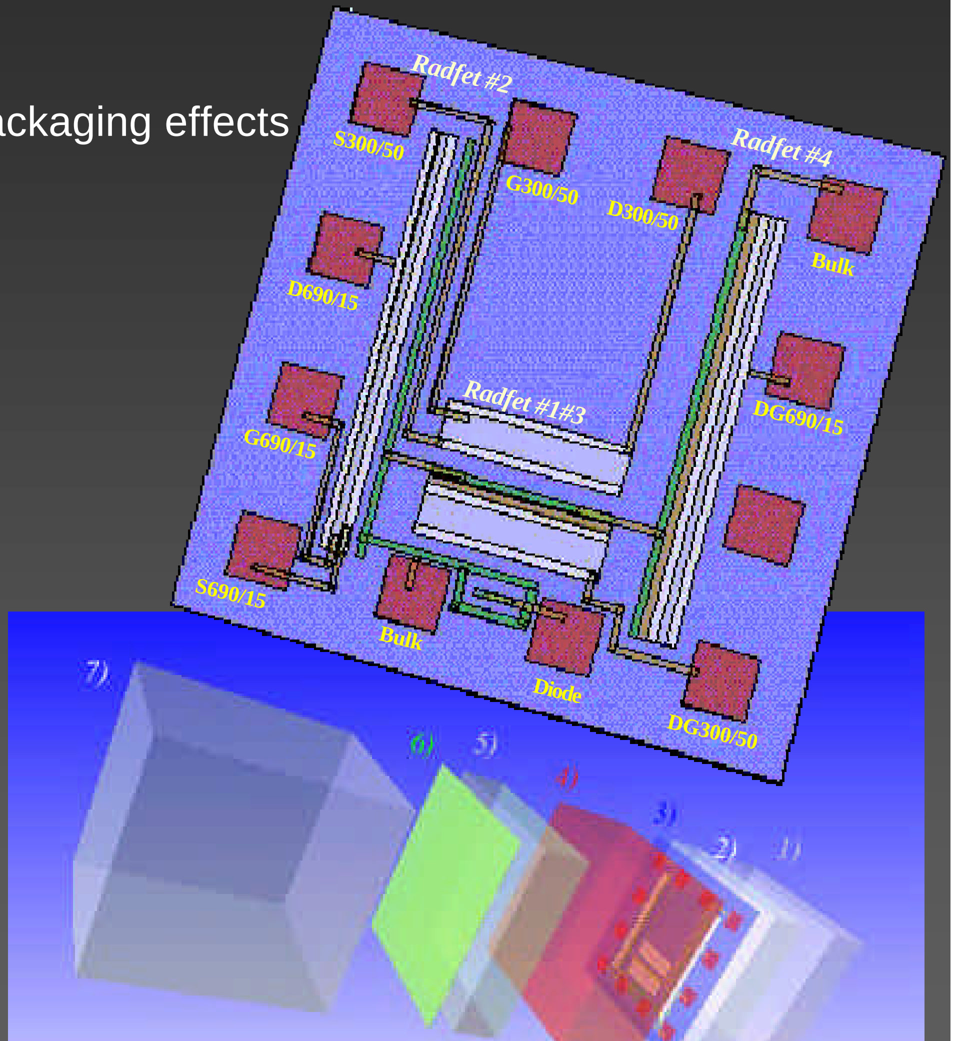
Radiation Environment Effects on Components (TEC-QCA)

- Component performance degradation
  - Simulation and prediction tools



K.Thiel and H.H.Fischer, Köln Univ.

- Packaging effects



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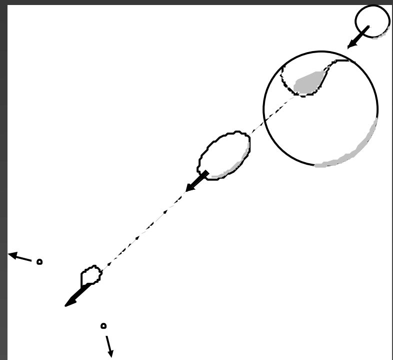
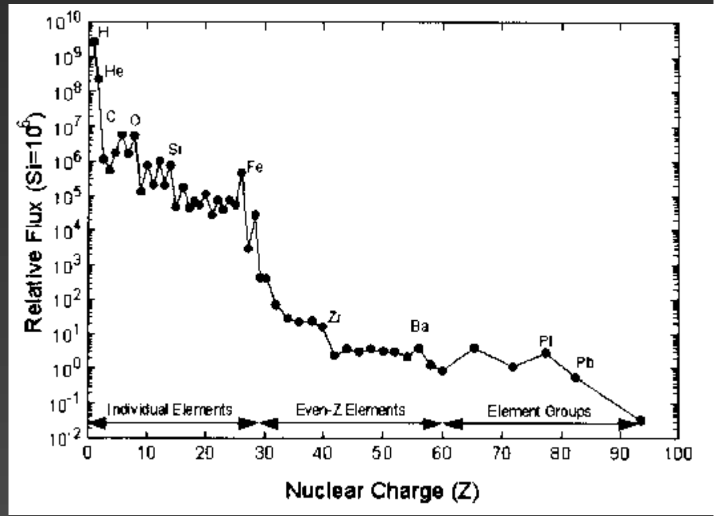
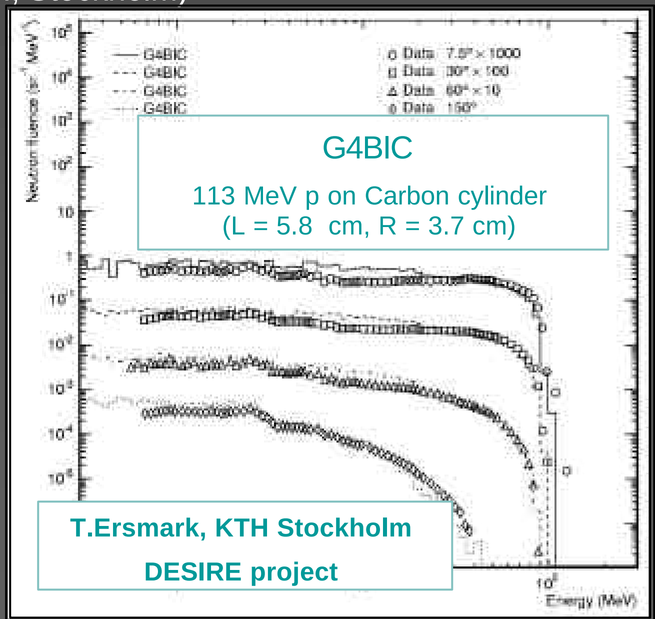
[3] PSI, Paul Scherrer Institut, CH-5232 Villigen, Switzerland

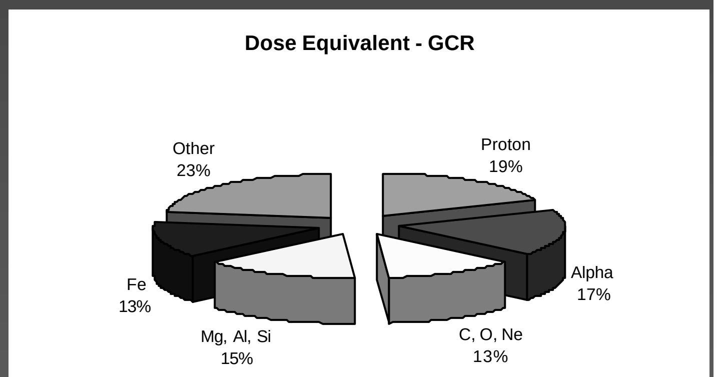
Geant4 physics for space applications
development and validation

- New physics models need to be included in the simulation tools
  - Process development
    - E.g. ion interactions: NASA NUCFRG2 Abrasion (P.Truscott, Qinetiq)
  - Model validation
    - E.g. neutron production from protons (T.Ersmark, KTH, Stockholm)





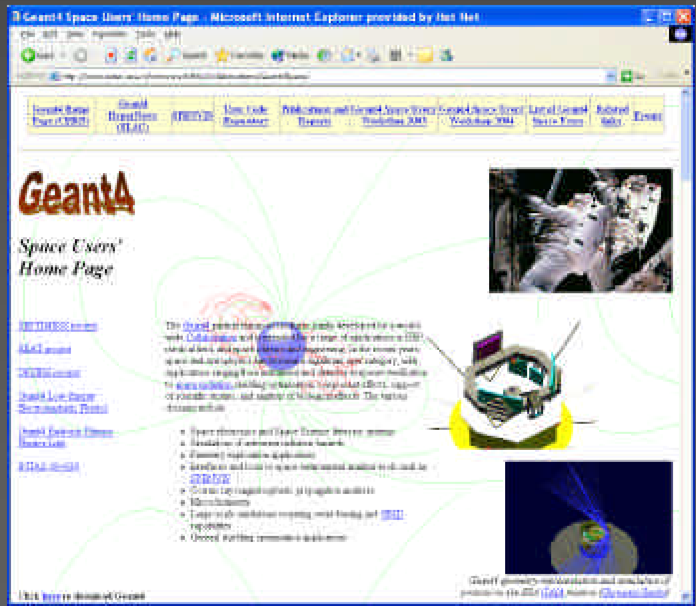




Data from W Schimmerling, J W Wilson, F Cucinotta, and M-H Y Kim, 1998.

Gathering the G4 Space Users' community

- Experience of the various groups around the world
- G4 Space Users' web page
  - Collection of topics, papers
  - Link to space related resources
  - http://www.estec.esa.int/wmwww/WMA/Collaborations/Geant4Space
- G4 Space Users Workshops
  - Jan 2003 – ESTEC
  - May 2004 – Vanderbilt
- Geant4 Technical Forum
  - Space User requirement collection



Particle environment simulation
Summary

- Successful application of G4 Monte Carlo techniques for the estimation of the HE Radiation Environment effects on satellites
  - Environment models
  - Radiation effects on components and detectors
  - Complete mission analyses and engineering tool development
- Geant4 description of spacecraft-particle interaction suitable for manned and un-manned mission analysis
  - Assessed EM physics performance
  - New promising hadronic models need
    - Still need validations and extensions (protons, ions)
- Need for engineering simulation tools
- Geant4 Space Users' world community
  - Coordination and partial funding

Space Weather

- *"conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health"*

  [US National Space Weather Programme]

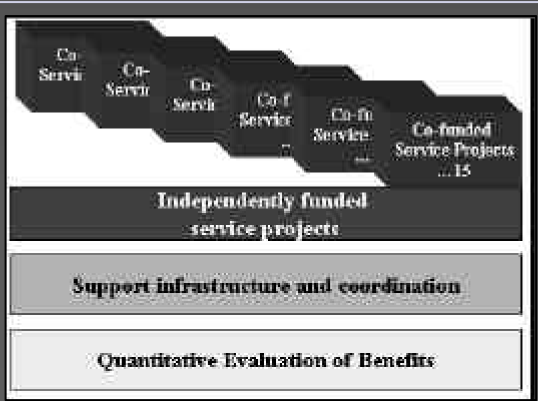
- Effects
  - Satellites affected by radiation, plasma, atmosphere, particulates;
  - Astronauts - ISS, future exploration missions;
  - Radiation hazards to air crew and avionics;
  - Ground power outages from currents induced in lines;
  - Disruption to communications relying on the ionosphere;
  - Disruption of navigation satellite signals (GPS - Galileo);
  - Prospecting;
  - Climate;

- http://www.esa.int/spaceweather

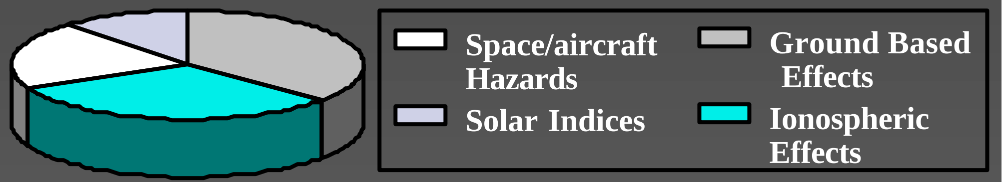



Space Weather GSP Initiative & Applications Pilot Project

- 1999-2001: ESA sponsored two studies
  - feasibility of a European Space Weather Programme
  - identified areas in need of further development e.g. data coverage, long term continuity, reliability and model accuracy.
  - Difficulties identified in finding committed users and hence problems in gauging the financial/strategic benefit of a space weather service.
- Where we are now: a 2-year co-funded applications based pilot project (2MEuro)



- Network of Service Development Activities (SDAs) for space weather applications with close links to users.
  - 26 activities: 16 ESA co-funded SDA activities + 10 independently funded activities. More being added..
- SDA's are participating in a common Space Weather European Network (SWENET).
  - Main tasks will include developing a data and service distribution infrastructure in consultation with the SDAs.
- Independent benefit assessment will establish the economic and other benefits of the services






http://www.esa.int/spaceweather

Summary

- ESA purpose: for exclusively peaceful purposes
  - Improve competitiveness of European industry
  - Conduct cost-effective research and development, and operations
  - Opportunities of collaboration with academia:
- Project support in the field of Space Environment and Effects
  - Needs emerged
    - Up-to-date data and models
    - Accurate effect prediction tools
- Dedicated software modules developed
  - Open source
  - Successful operation
- Coordination of/with relevant communities
  - Plasma - SPINE
  - HEP - Geant4
  - Services - Space Weather