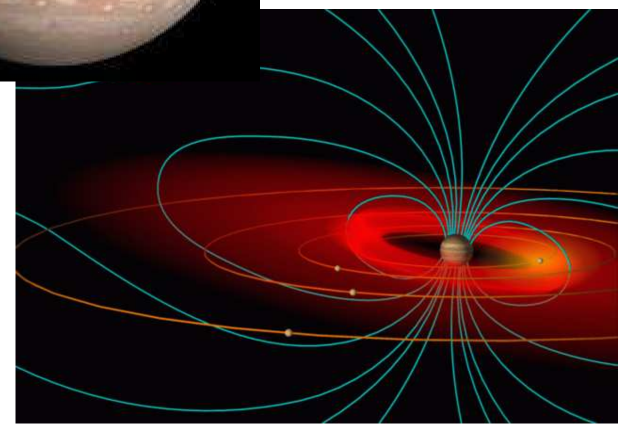
The JORE^{2}M^2 Project: Jupiter Environment, Effects and Shielding Prediction Models for SPENVIS



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9 June 2010

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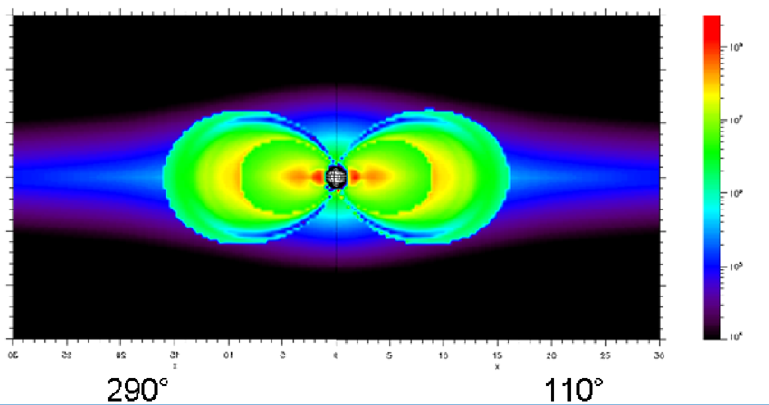
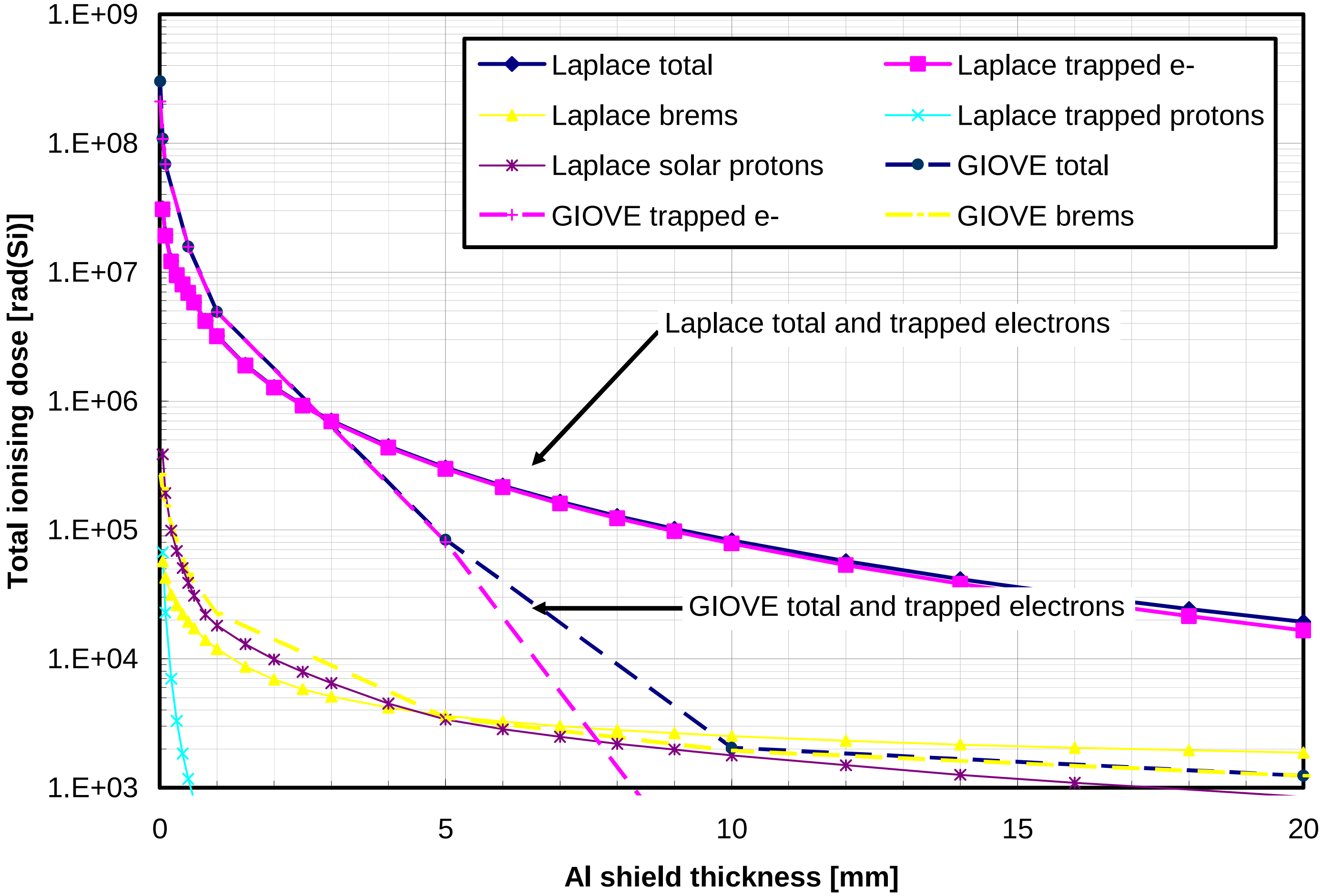


QinetiQ

www.QinetiQ.com

Effects of the Jovian Radiation Environment
Comparison with MEO (GIOVE solar max, 939 days)



Data from J Sørensen and G Santin (Laplace), and QinetiQ (GIOVE, VALCOMPT project)

Objectives and Focus

- **Assess the requirements** for radiation and plasma **environment** models, and **effects and mitigation** tools for future Jupiter-system missions (including Jupiter flyby), and **review existing models and data**.
- New model developments:
  - **JOSE**: Trapped proton and electron belt models based on all relevant data from Jupiter-system instruments
  - **PLANETOCOSMICS-J**: An updated Geant4/PLANETOCOSMICS application to model radiation environment in vicinity of Galilean moons
  - **SHIELDOSE-2Q:** Updated SHIELDOSE-2 to treat additional shield and target materials, and extend electron energy range
  - **GARSO**: Shield optimisation tool based on Genetic Algorithms and MULASSIS
  - **DG83**: Divine and Garrett model for warm and cold plasmas
- All tools and models are being interfaced to SPENVIS
  - Note **PLANETOCOSMICS-J** and **GARSO** tools **require lengthy simulations**, therefore the user will also be able to download software and run locally with macrofiles generated by SPENVIS GUI interface

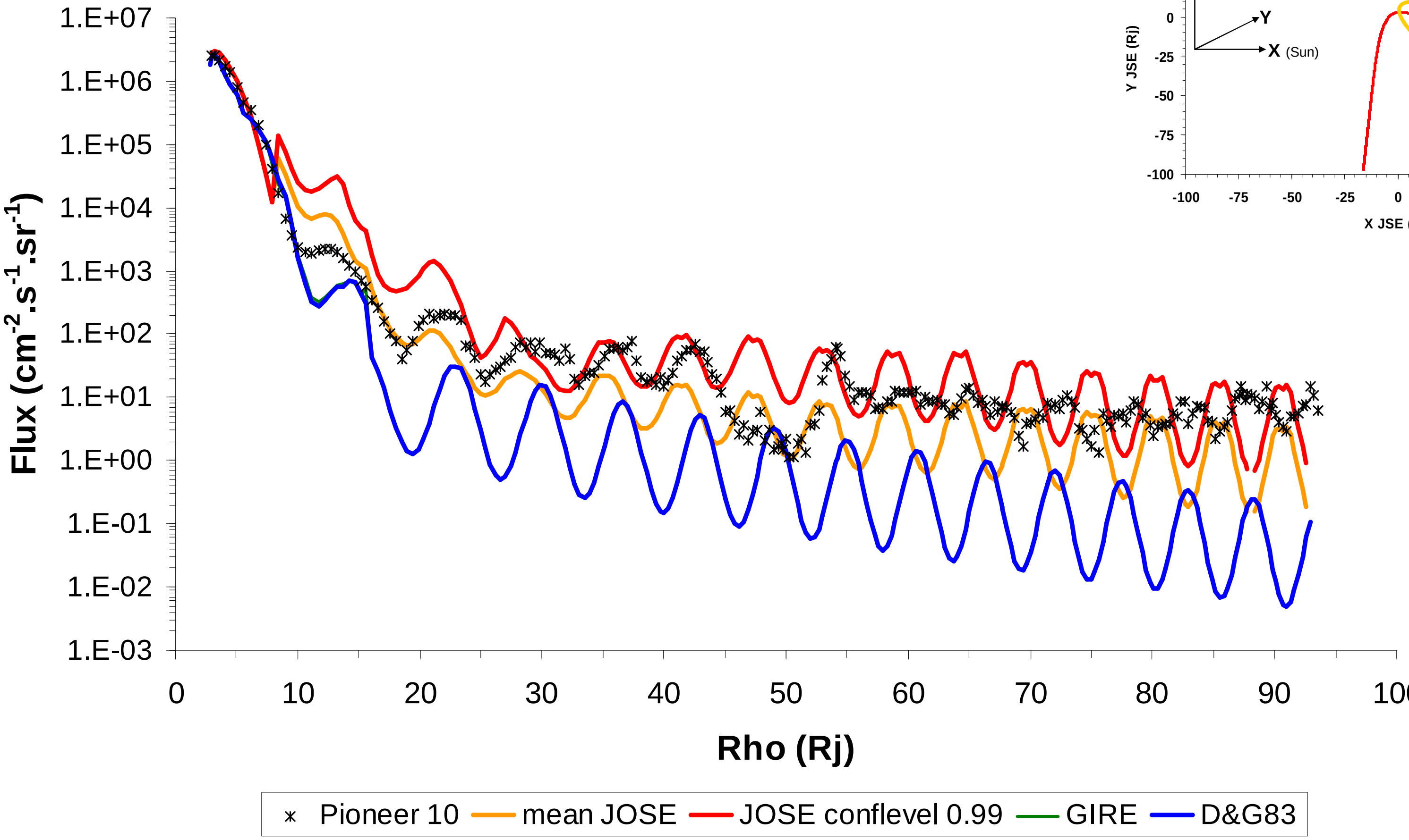
JOSE – Jovian Specification Environment Model

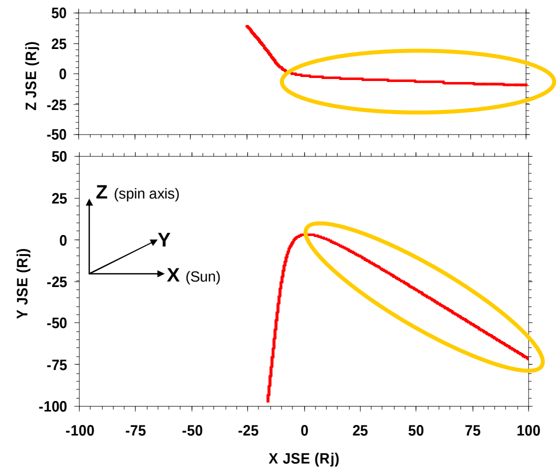
- JOvian Specification Environment model developed by ONERA
- Flux predictions for electrons and protons
- Covers Jupiter atmosphere to 100 R_j
- All relevant in-situ observation data used; electron data based on Galileo/EPD data
- Mean environment model & confidence level model, essential for engineering specification
- L > 10, good constraints at energies between 20 keV and 10 MeV, reasonable confidence in the model expected over to ~10-30 MeV for electrons and 1MeV for protons

JOSE Validation example for electrons

Comparison of JOSE with P10 data and other model

Flux of electrons > 21 MeV
along the inbound trajectory of Pioneer 10





PLANETOCOSMICS-J Galilean Moon Environment Tool

Update L Desorger's PLANETOCOSMICS model, a **Geant4 application** which simulates **nuclear** and **electromagnetic interactions** of particles in planetary magnetic fields and atmospheres

- PCJ uses and elements of **SAPRE** to positions of the Galilean moons
- Models for **Jovian internal** and **external** fields
  - Allowed fields for PLANETOCOSMICS: P11, O4, O6, Ulysses, VIP4
  - In addition, user can now select Jovian external field (Khurana, 1997 and 2003 models)
- Models Ganymede and Io **internal fields** (Kivelson, Khurana & Volwerk (2002) and Khurana (1996) respectively)
  - Ganymede field re-implemented: previously specification implemented in FORTRAN 90 called from PLANETOCOSMICS, but now field fully implemented in C++
- General model for the **induced magnetic field** derived from Zimmer, Khurana & Kivelson (2000)

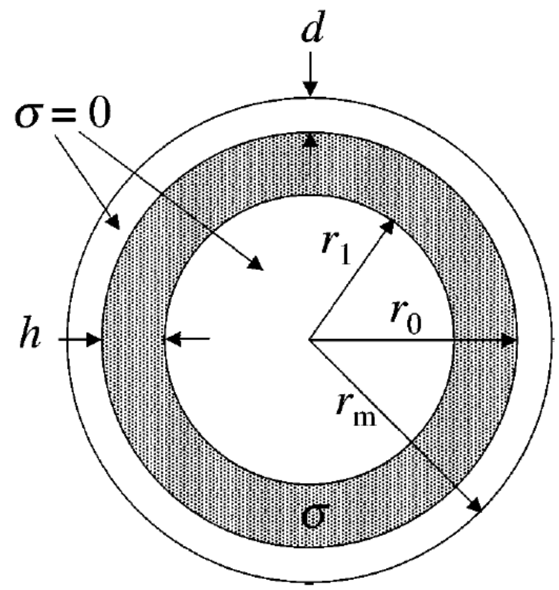
PLANETOCOSMICS-J Induced Magnetic Fields

- Based on Zimmer, Khurana & Kivelson
- B_{prim} is amplitude of variations in Jupiter's field at the moon

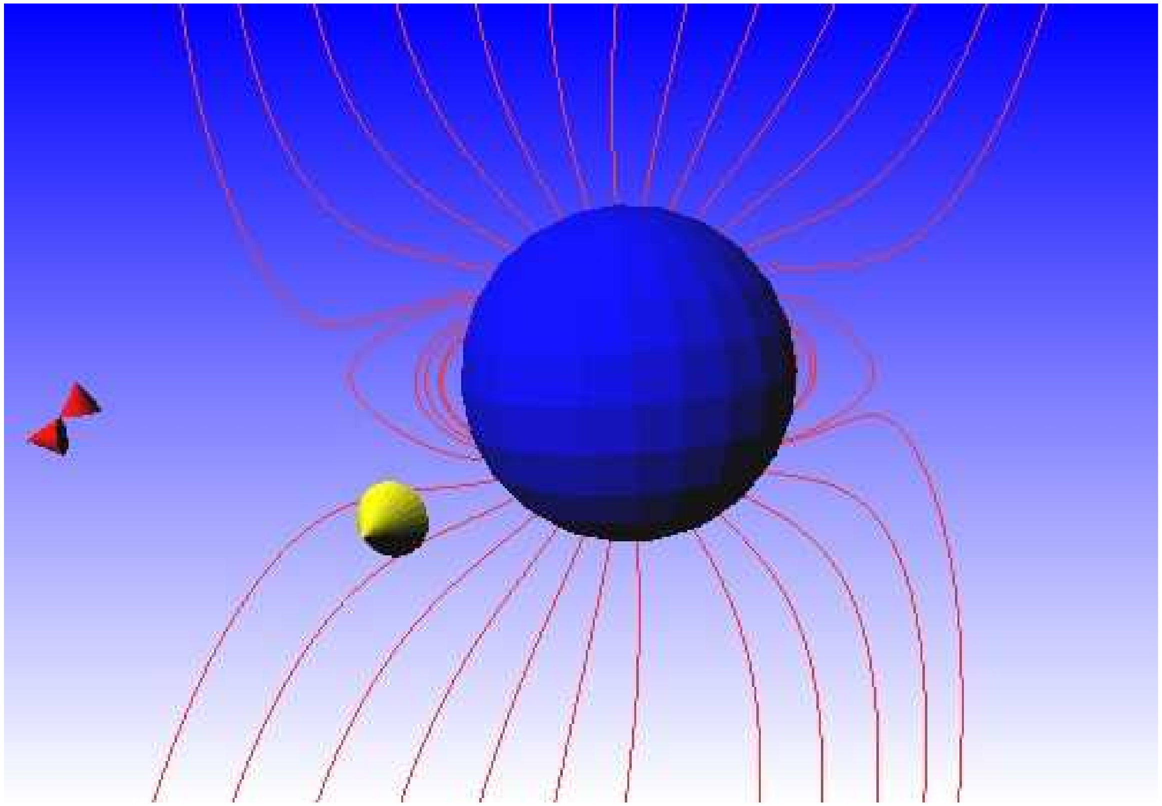
$$\mathbf{M} = -\frac{4\pi}{\mu_0} A e^{i\phi} \mathbf{B}_{\text{prim}} r_{\text{m}}^3 / 2,$$

$$\mathbf{B}_{\text{sec}} = \frac{\mu_0}{4\pi} [3(\mathbf{r} \cdot \mathbf{M})\mathbf{r} - r^2 \mathbf{M}] / r^5$$

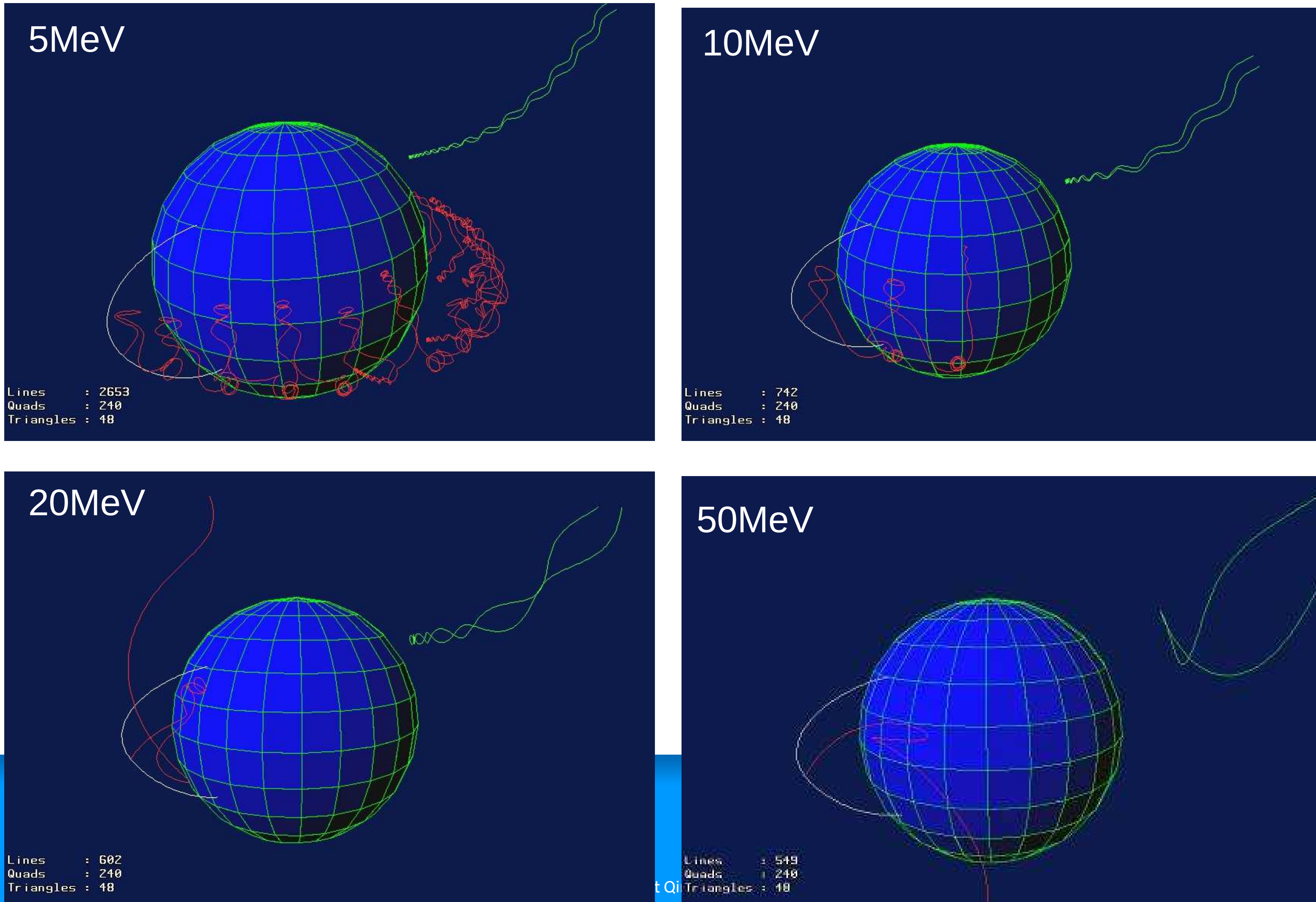
- Coefficient A and phase lag ø determined by geometry of and conductivity of sub-surface oceans – user defined in PLANETOCOSMICS-2.0J !!
- Uses ONERA Jupiter field models to determine B_{prim} as a function of time (B-<B>)



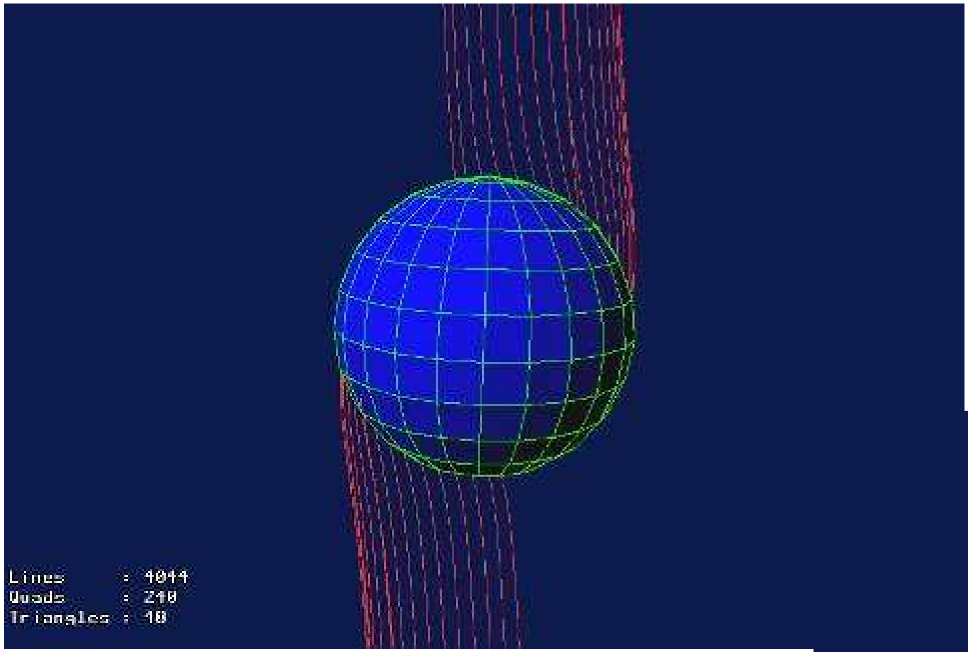
PLANETOCOSMICS-J Total field for Ganymede

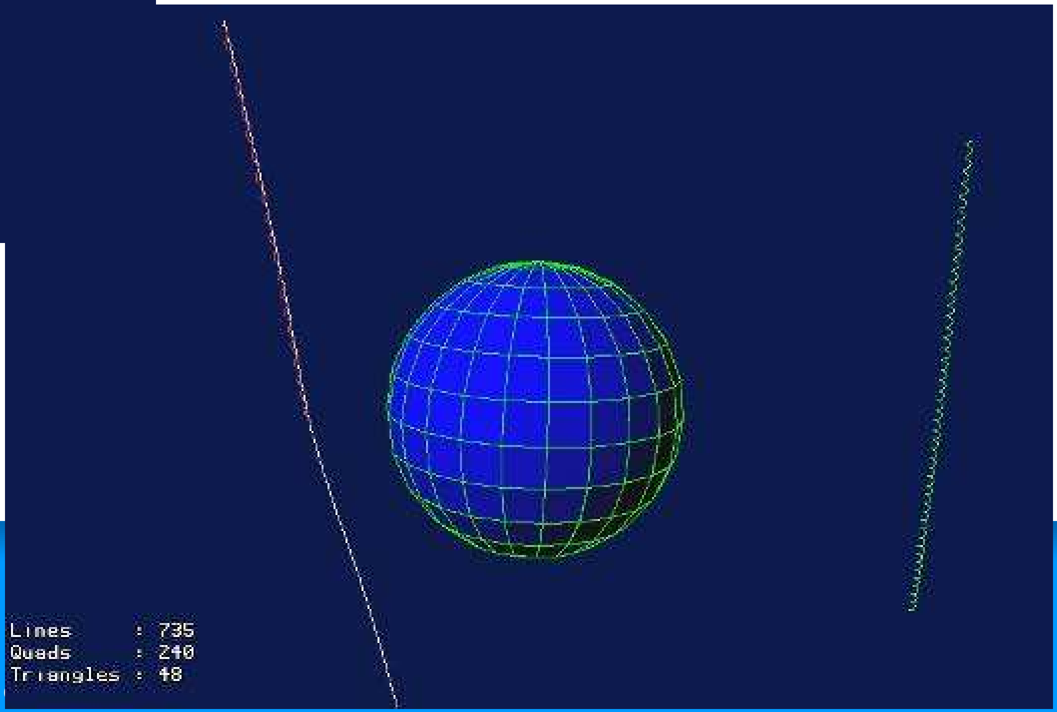


PLANETOCOSMICS-J Motion of electrons in Ganymede field



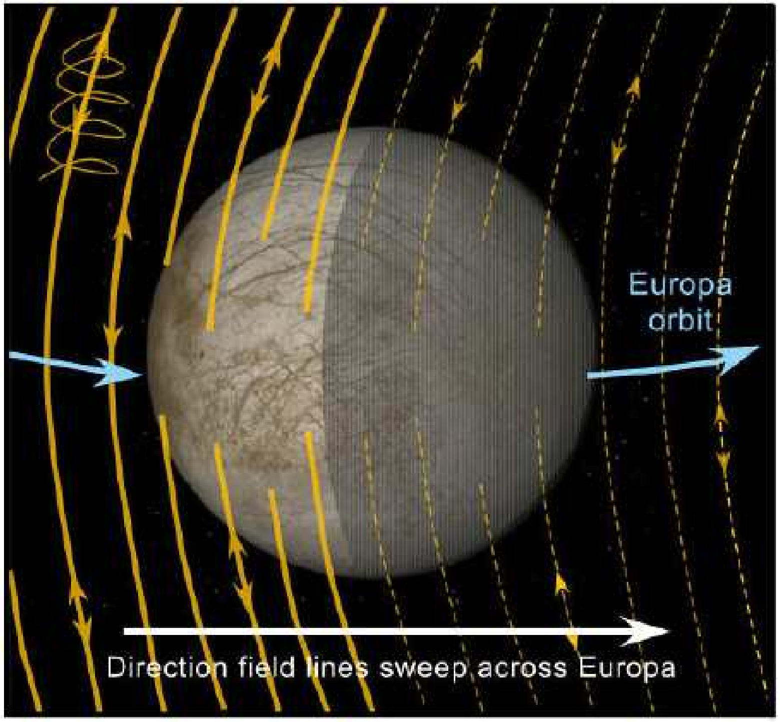
PLANETOCOSMICS-J Motions of electrons in Europa field (15MeV electrons)





PLANETOCOSMICS-J Depletion of trapped radiation belts

- Added complexity from the slower orbital period of Europa with respect to the combined effects:
  - rotation of the Jovian magnetic field
  - drift period of the particles
- Since the field lines of Jupiter's sweep from the trailing hemisphere to the leading hemisphere, the plasma overtakes the moon, resulting in
  - particle deposition in the trailing hemisphere
  - Depleted particle populations at leading hemisphere

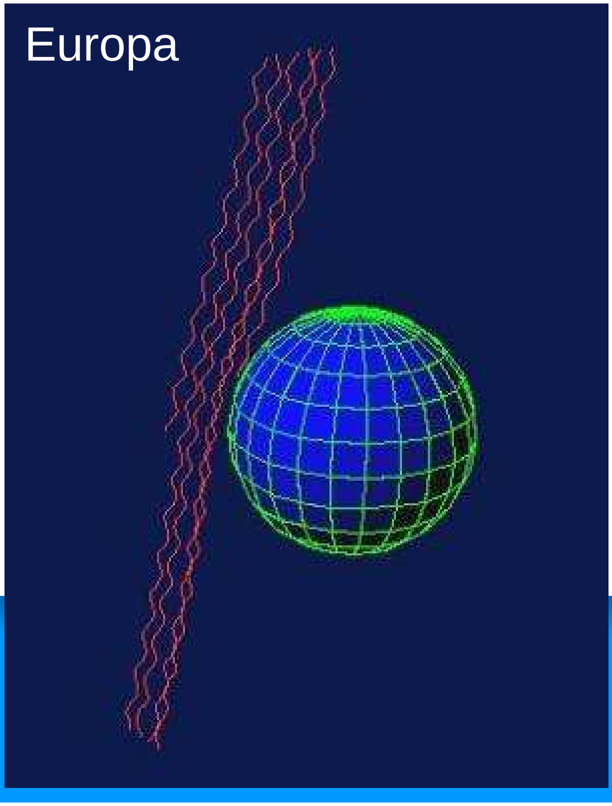


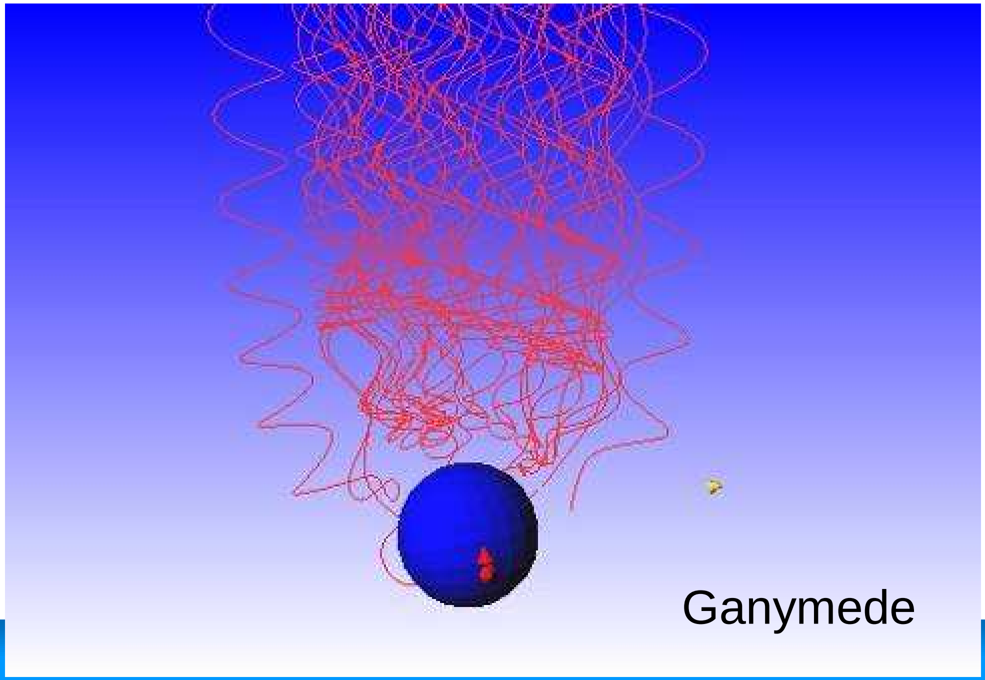
PLANETOCOSMICS-J Depletion of trapped radiation belts

- Algorithm included to calculate the drift of particles relative to the moons between bounce
- No need to simulate whole of Jupiter field

$$\tau_b = \frac{4r_0}{v}\int_{\theta_m}^{\pi/2} \frac{\sin\theta\,(1+3\cos^2\theta)^{\frac{1}{2}}\,d\theta}{\left(1-\frac{\sin^2\alpha_0\,(1+3\cos^2\theta)^{\frac{1}{2}}}{\sin^6\theta}\right)^{\frac{1}{2}}}.$$

$$\langle\tau_d\rangle \approx \frac{\pi q B_E R_E^2}{3LW}(0.35 + 0.15\sin\alpha_{eq})^{-1}$$





SHIELDOSE-2Q

SHIELDOSE-2 calculates depth-depth (TID) information for Al

- 1D shielding: finite slab, semi-infinite slab, solid sphere and spherical shell (latter two by transformation of slab results)
- based on tabulated data from Monte Carlo electron-photon transport code ETRAN: 50MeV

SHIELDOSE-2Q (SD2Q) prototype available with complete shield and target database

- Very similar in look-and-feel to the user as SD2 but with greater capability
- Comparisons perform with MULASSIS simulations

SD2Q Development of database – Shielding materials

- Simulations for shields:
  1. Aluminium (Z=13)
  2. Titanium (Z=22)
  3. Iron (Z=26)
  4. Tantalum (Z=73)
  5. 80% tungsten (Z=74) + 20% copper (Z=29) CW80 alloy
  6. Al/Ta Combination, using 1mm Al at front

SD2Q Development of database – Target materials (IDET designation)

Standard SD2 targets

1. Al Detector
2. Graphite
3. Si Detector
4. Air Detector
5. Bone Detector
6. Calcium Fluoride
7. Gallium Arsenide
8. Lithium Fluoride
9. Silicon Dioxide
10. Tissue Detector
11. Water Detector

Additional SD2Q targets

12. Polyimide
13. Epoxy
14. Hafnium Dioxide
15. Silicon Carbide
16. InGaAs
17. HgCdTe
18. Sodium Iodide
19. Magnesium Oxide
20. Germanium
21. Titanium
22. Iron
23. Tantalum
24. Tungsten
25. CW80 Alloy
26. Silicon NIEL
27. Gallium Arsenide NIEL

NOTE: NIEL calculations approaches are experimental and subject to validation

SD2Q Development of database – Target materials

Calculations involve integration of Monte Carlo / analytical model calculated spectra over energy-deposition coefficient (*e.g.* $S_{col}(E)$, $S_{el}(E)$ ...)

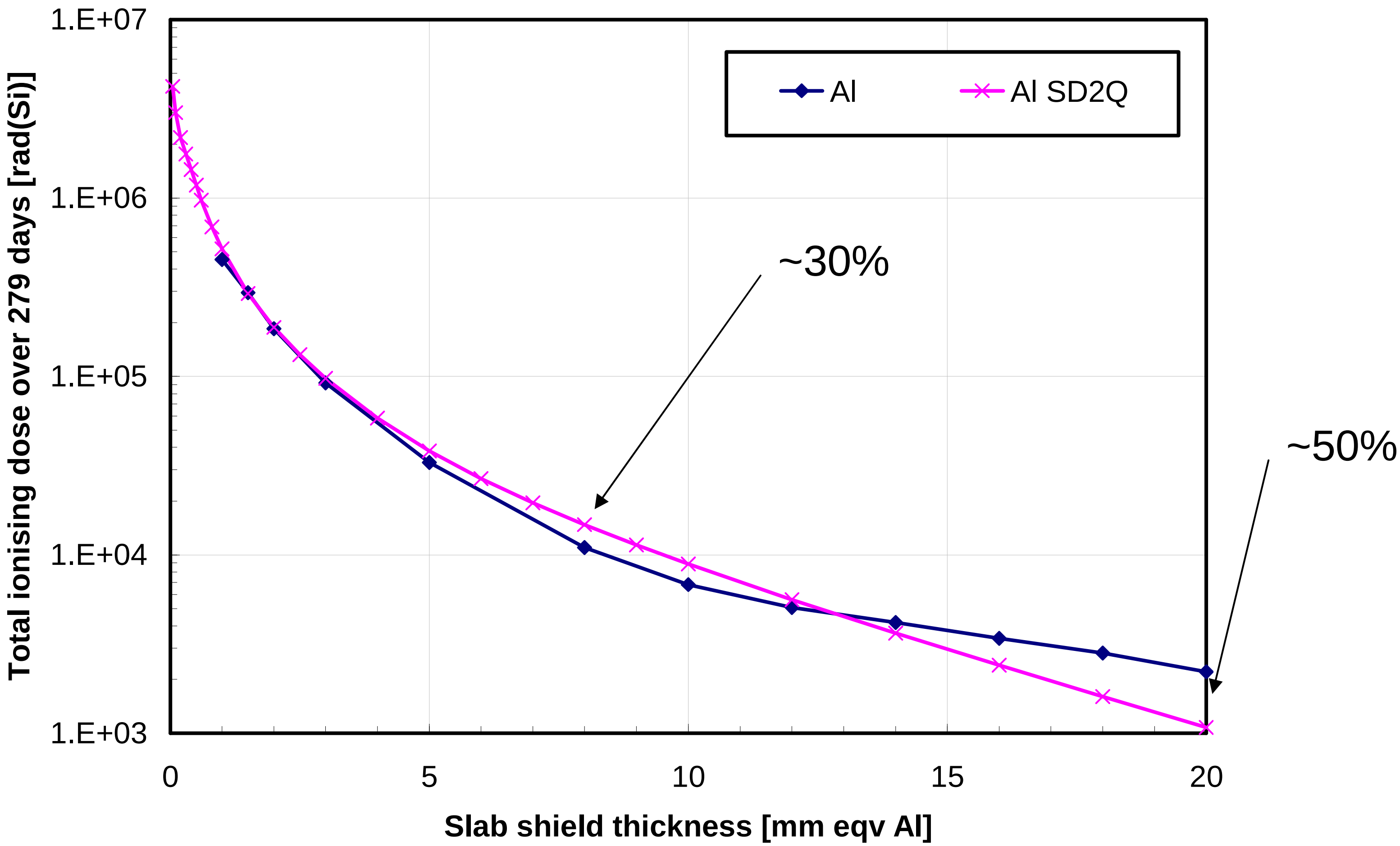
Due to the range of target materials, *extensive set of coefficients* had to be developed for interactions:

- **Electrons** (1keV to 1GeV), Stopping power data from **NIST ESTAR** data (allows definition of any material)
- **Photons** (1keV to 1GeV), mass energy absorption coefficients from **NIST** data, with *linear additivity*.
- **Protons** (1keV to 10GeV), Stopping power data from **NIST PSTAR** and Ziegler et al's **SRIM2008**

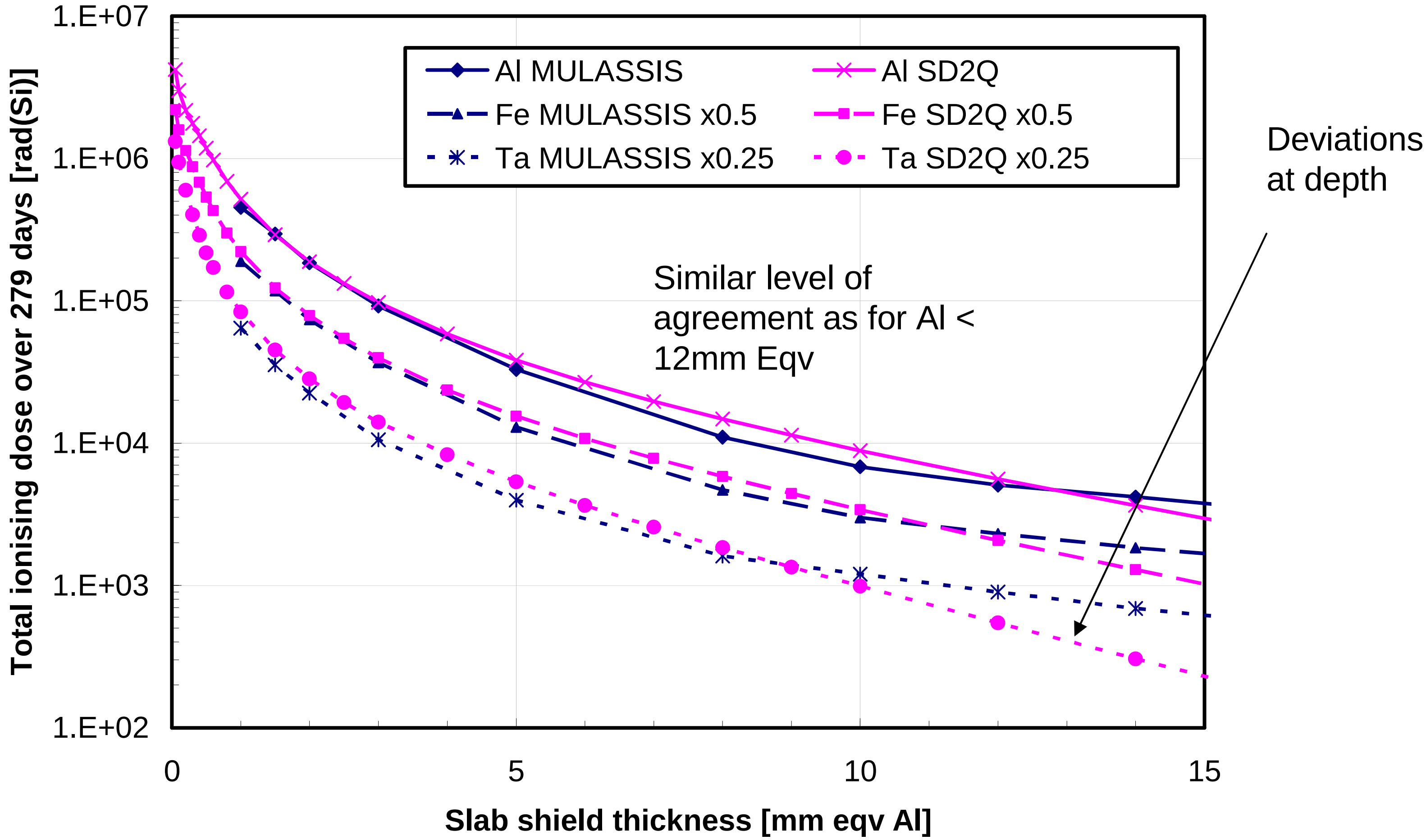
Errors in original data removed:

- Swapped brems coefficient data for finite and semi-infinite slab shields
- Some of 0.002MeV electron dose data set to 0.005MeV data
- In some other areas, dose coefficients for target materials behind finite slab larger than for semi-infinite slabs

SD2Q Verification and validation – electron/brems dose



SD2Q Verification and validation – electron/brems dose

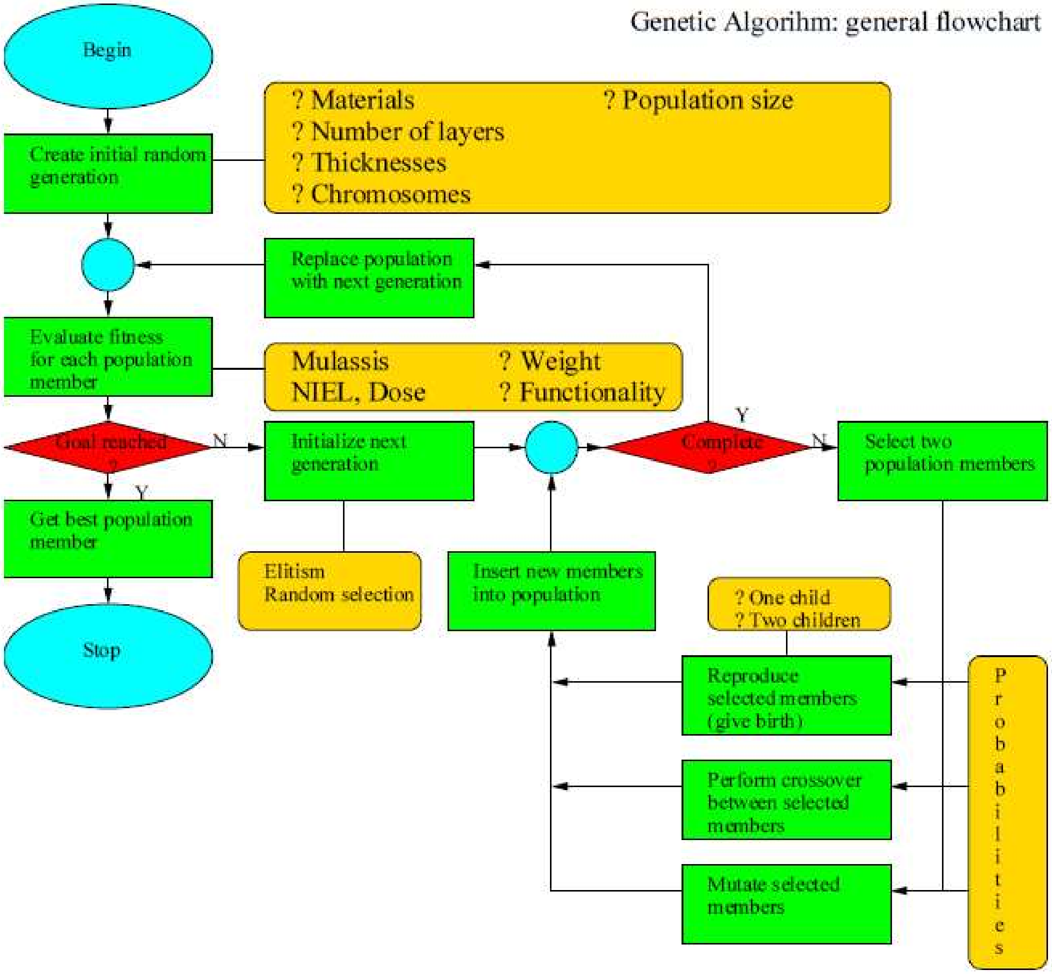


GARSO Genetic Algorithm Radiation Shield Optimiser using MULASSIS

- Efficiency of electron shield strongly dependent on shield composition (material, thickness, order, …)
- Developed originally as prototype/demonstrator for REAT-MS and tested only for NIEL dose on Giove-A (electron-dominated environment)
- Genetic Algorithm to select population and MULASSIS to assess shield performance
- Enhancements to help
  - Portability (Linux & Windows)
  - User-selectable parameters without recompilation
  - simplification of user parameters / interface
  - MULASSIS is run for trapped electrons, trapped protons and solar protons
  - fitness assessment to include NIEL and TID optimisation

GARSO Genetic Algorithm Radiation Shield Optimiser using MULASSIS

- Uses a genetic algorithm software package + MULASSIS to help identify optimal shield configurations
- Use cases
  - Case 1: Identify lowest-mass design meeting a specific shielding performance
  - Case 2: Best shielding performance for a given areal mass budget



DG83 Plasma Model Overview

Implementation of Divine & Garrett 1983 (DG83) model for the warm (intermediate) and cold plasma environments:

- DG83 Warm plasma model for protons, with electron plasma set 3x protons (500 eV < E < 100 keV)
- DG83 Cold plasma model divided into four regions:
  1. inner plasmasphere (1 < *r* < 3.8 RJ);
  2. Io plasma torus (3.8 < *r* < 7.9 RJ), which is subdivided:
     - cool (3.8 < *r* < 5.5 *RJ*) torus;
     - warm (5.5 < *r* < 7.9 *RJ*) torus;
  3. inner (7.9 < *r* < 20 *RJ*) disc;
  4. outer (20 < *r* < 170 *RJ*) discs.
- Note in DG83:
  - Warm and cold plasma environment defined by r, λ, l and z_0 Systems III (1965) coordinates

Implemented as open source FORTRAN subroutines, called from SPENVIS for each step in spacecraft trajectory

DG83 Plasma Model Status of Development/Implementation

- Plasma model has implemented as a series of subroutines in FORTRAN 90 called from SPENVIS for each step in spacecraft trajectory
- Input coordinates to main routine are System III (1965)
  - R [R_j]
  - λ, latitude [degrees]
  - L, longitude [degrees]
- Output:
  - Number density $N_w(0)$ for warm electrons, and $N_w(1)$ for warm protons [/cm^3]
  - Number density for cold plasma $N_c(k)$ [/cm^3]:
  - k=0: e-, k=1: p+, k=2: O+, k=3: O++, k=4: S+,k=5: S++, k=6: S+++, k=7: Na+
  - Plasma temperature kBT [MeV]
  - V_ϕ bulk velocity? [km/s]

Summary

- JORE^{2}M^2 Project has developed several new tools to:
  - Quantify the environment, including complex field and material effects in vicinity of moons (JOSE & PLANETOCOSMICS-J)
  - Examine shielding strategies, including different material types and optimised composition (SD2Q and GARSO)
- These tools are being integrated into SPENVIS
  - Accessibility and easy-to-use
  - take advantage of interfaces to existing tools
- User will also be able to download software and run locally with macrofiles generated by SPENVIS GUI interface

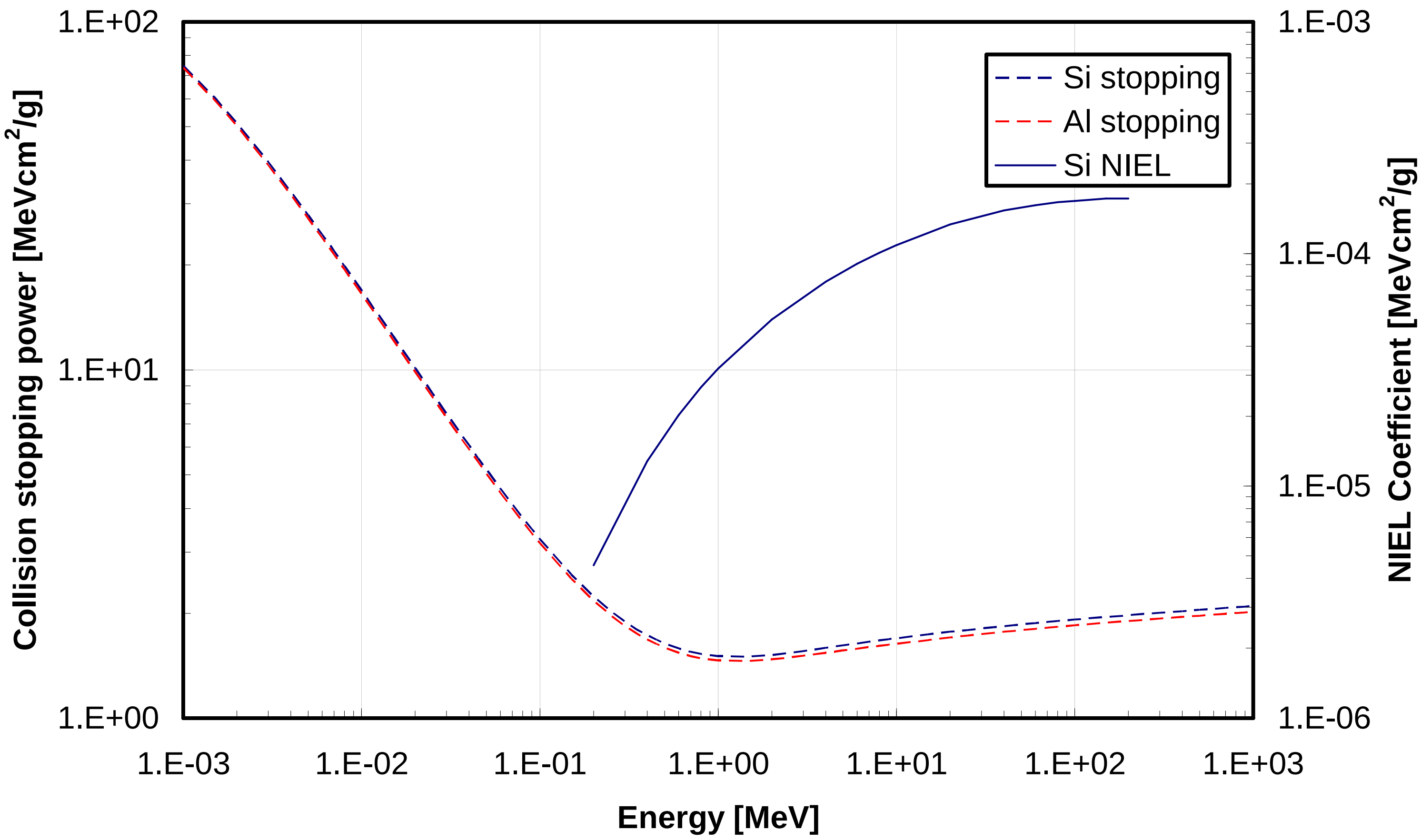
Thanks!

The authors would like to thank

- Dr Laurent Desorgher (SpaceIT, Switzerland) for useful discussions on the PLANETOCOSMICS code
- Dr Steve Seltzer (NIST, USA) for assistance in understanding the data content of SHIELDOSE-2

Backup slides

SD2Q Interpolation for stopping power vs. NIEL



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