STATUS OF THE GALILEO INTERIM RADIATION ELECTRON MODEL

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Measurements of the high energy, omni-directional electron environment by the Galileo spacecraft Energetic Particle Detector (EPD) were used to develop a new model of Jupiter's trapped electron radiation in the jovian equatorial plane for the range 8 to 16 Jupiter radii (1 jovian radius = 71,400 km). 10-minute averages of these data formed an extensive database of observations of the jovian radiation belts between Jupiter orbit insertion (JOI) in 1995 and 2002. These data were then averaged to provide a differential flux spectrum at 0.174, 0.304, 0.527, 1.5, 2.0, 11.0, and 31 MeV in the jovian equatorial plane as a function of radial distance. This omnidirectional, equatorial model was combined with the original Divine model of jovian electron radiation to yield estimates of the out-of-plane radiation environment. That model, referred to here as the Galileo Interim Radiation Electron (or GIRE) model, was then used to calculate the Europa mission dose for an average and a 1-sigma worst-case situation. The prediction of the GIRE model is about a factor of 2 lower than the Divine model estimate over the range of 100 to 1000 mils (2.54 to 25.4 mm) of aluminum shielding, but exceeds the Divine model by about 50% for thicker shielding. The model, the steps leading to its creation, and relevant issues and concerns are discussed. While work remains to be done, the GIRE model clearly represents a significant step forward in the study of the jovian radiation environment, and it is a useful and valuable tool for estimating that environment for future space missions.

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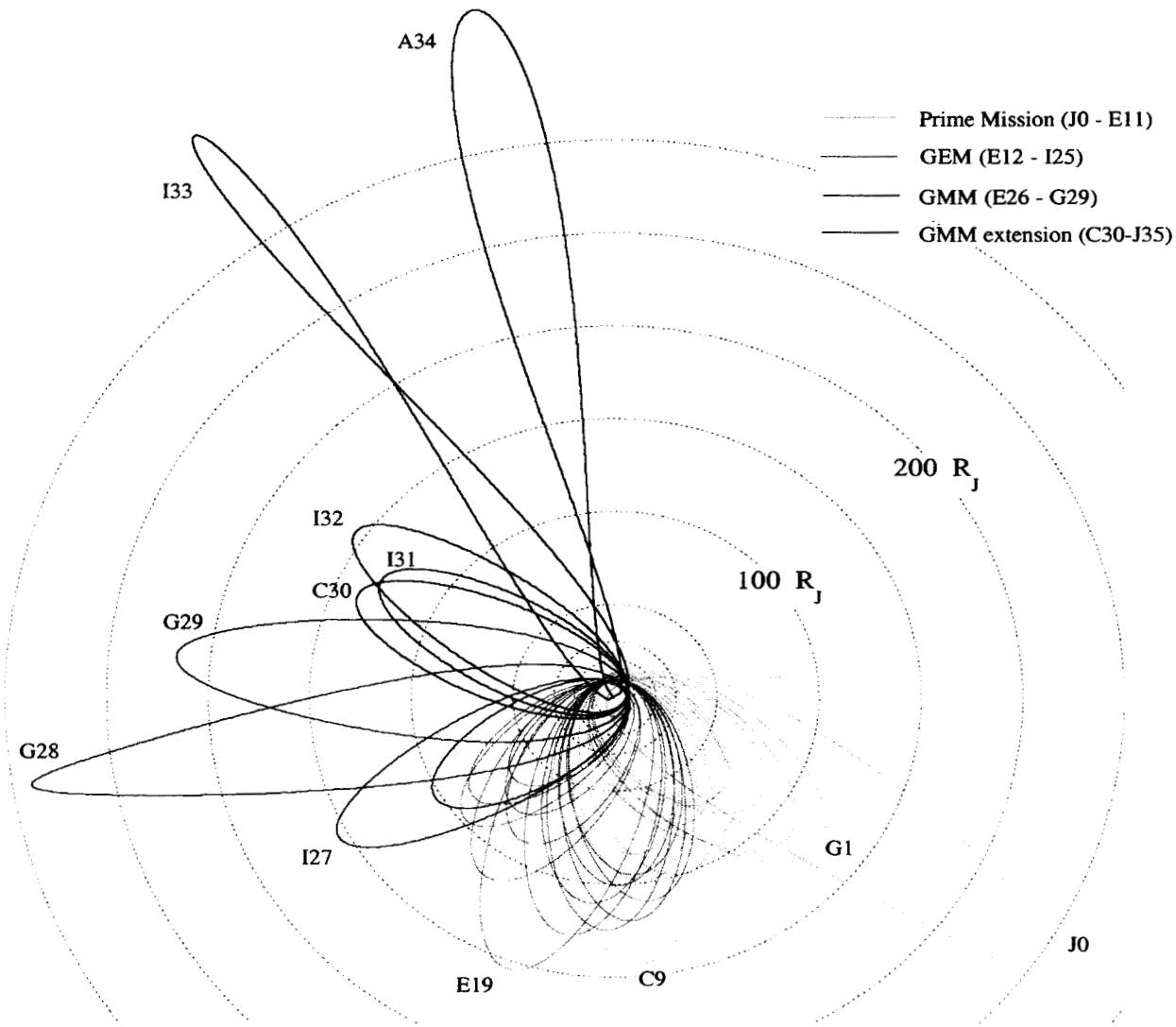
Galileo Interim Radiation Electron Model

GALILEO ORBITS



Galileo Interim Radiation Electron Model

The first step in developing the model was to combine the high-energy particle count rate data from the Johns Hopkins University Applied Physics Laboratory (JHU/APL) EPD with data on the location and magnetic environment at the spacecraft—specifically, the position of the Galileo spacecraft in various coordinate systems and the magnetic field vector (as modeled by the VIP4 magnetic field model) at the spacecraft. 10-minute averages of these data formed an extensive database of observations of the jovian radiation belts between Jupiter orbit insertion (JOI) in 1995 and 2002 (data are still being collected as of the date of this report).

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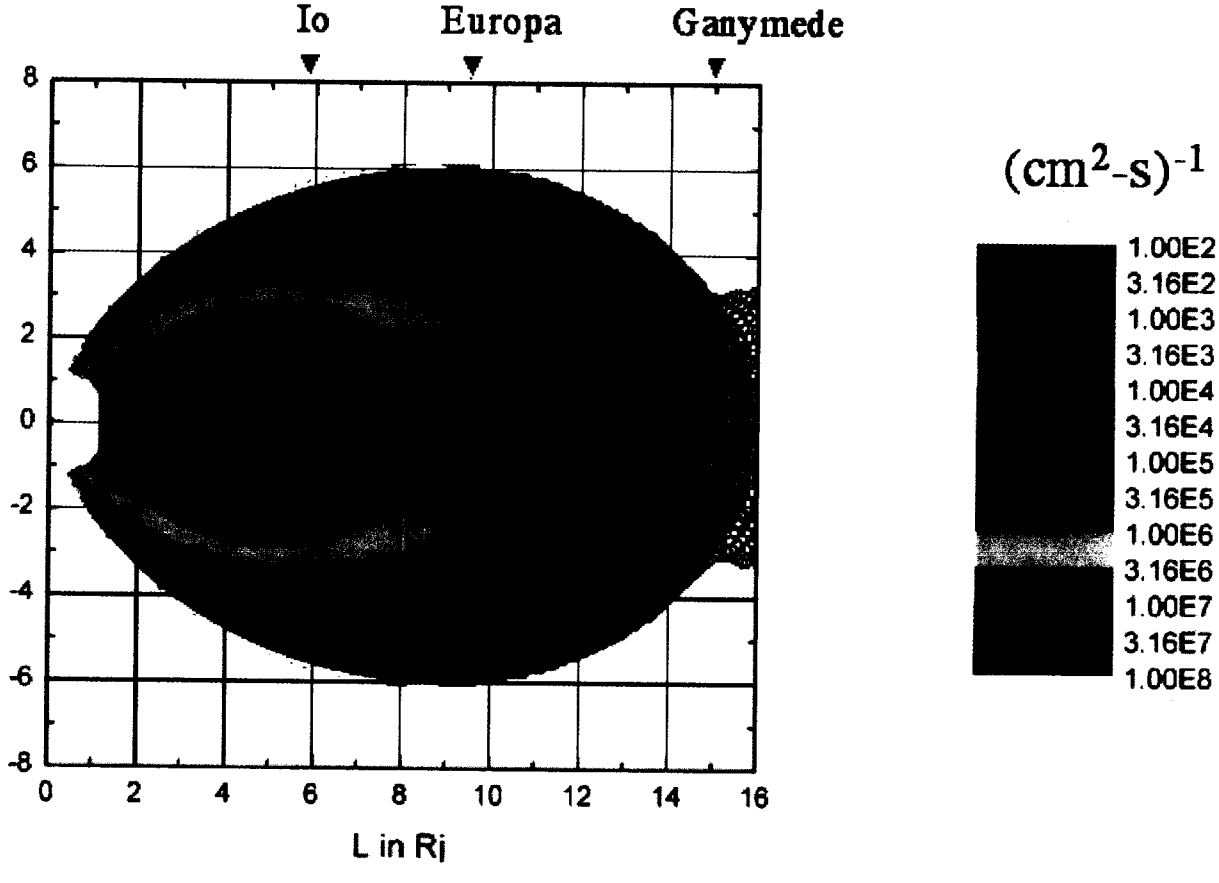
Galileo EPD Data Overlaid on Jovian Radiation Belts



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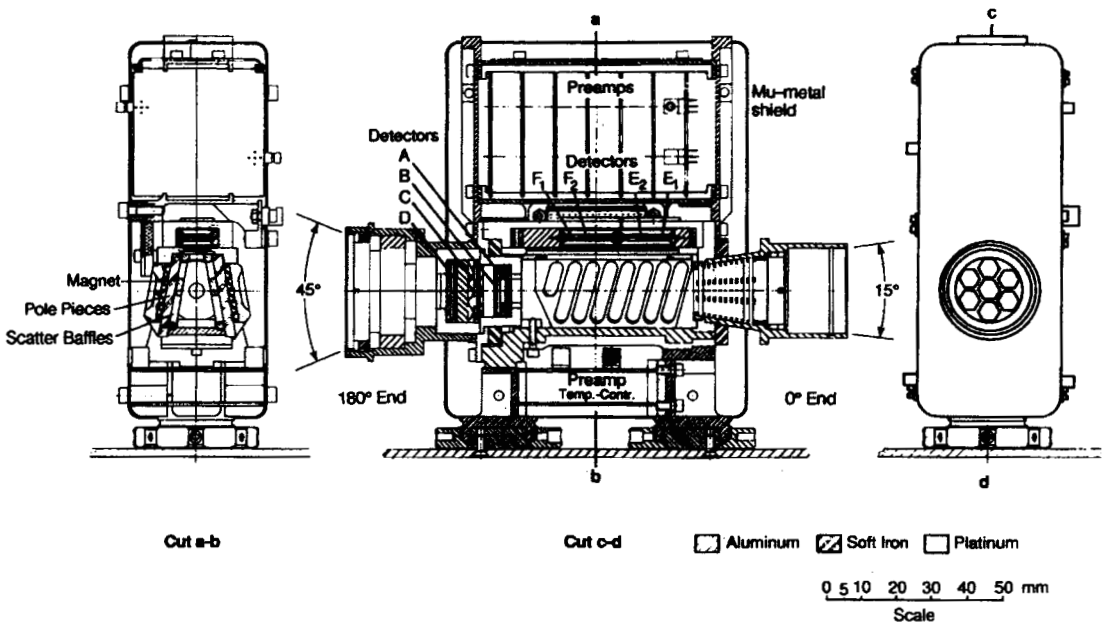
APL/JHU ENERGETIC PARTICLE DETECTOR



Channel Name	Species	Nominal Energy Range (MeV)	Channel Logic
B0	Z=1	3.20-10.1	A7 B1 NC2
B1	Electrons	1.5-10.5	A2 NA4 B1 NB2 NC2
DC0	Z≥1	14.5-33.5	NB1 D2 NC1
DC1	Z≥1	51-59	NB1 C2 D1
DC2	Electrons	≥2	NB1 D1 ND2
DC3	Electrons	≥11	NB1 C1 NC2 D1

Description of the LEMMS high energy electron and protons channels (Williams et al., 1992).

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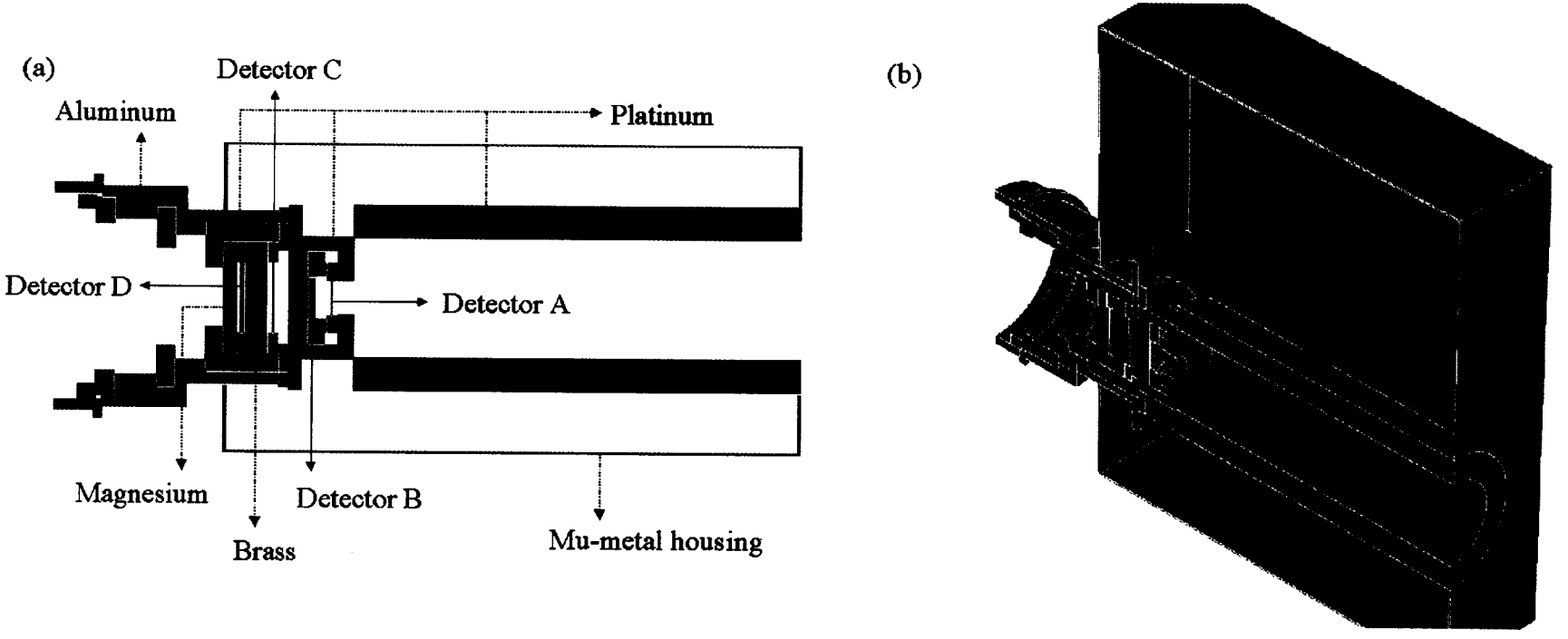
APL/JHU ENERGETIC PARTICLE DETECTOR



LEMMS modeling used in the MCNP/MCNPX simulations:
(a) Cross sectional view and (b) Iso-view

Galileo Interim Radiation Electron Model

The second step was to determine the relationships necessary to convert the raw EPD count rates to scientific flux units. The EPD data are available in discrete channels ranging from ~0.2 MeV up to over 11 MeV. The high-energy channels were not as well calibrated as desired before the launch of Galileo. To improve the calibration, a Monte Carlo radiation transport analysis (see Jun et al., 2002) was performed on the EPD design to determine the instrument response to the energetic electrons and protons in the jovian environment. The three-dimensional Monte Carlo radiation transport codes, Monte Carlo N-Particle Transfer Code (MCNP) version 4B (for electrons) and MCNPX version 2.2.3 (for protons), were employed for this purpose. The results of the study are presented in the form of "geometric factors" for the high-energy channels. Of specific interest to the current study are the B1, DC2, and DC3 channels for electrons as these bracket the energy range of most interest for jovian dose calculations. These channels had thresholds of approximately 1.5, 2.0, and 11.0 MeV respectively. The geometric factor corresponding to each channel is the energy-dependent detector response function that relates the incident particle fluxes to instrument count rates. As demonstrated in Jun et al., 2002, the trend of actual data measured by the EPD was successfully reproduced using the geometric factors obtained by the MCMP/MCNPX programs and the experimenter-provided drawings.

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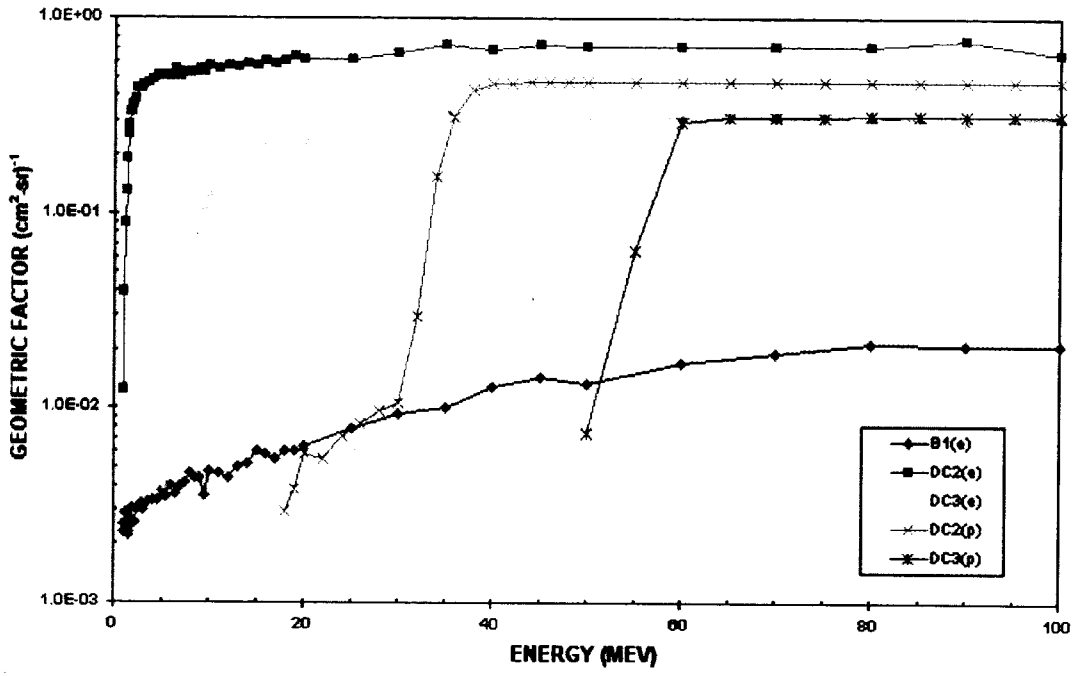
GEOMETRIC FACTORS



$$(cts/s)_{APL} = \int_0^\infty \frac{dI(E)}{dE} G(E)\cdot dE = J_0 \int_0^\infty \left(E_i/E_0\right)^{-X} G(E)\cdot dE \cong J_0 \sum_{i=1}^{\infty} \left(E_i/E_0\right)^{-X} G(E_i)\cdot \Delta E_i$$

Where:

E_i = Energy steps (E_1 = 1 MeV here)

E_0 = 1 MeV

$(cts/s)_{APL}$ = Counts per second from EPD channels (B1, DC2, DC3)

$I(E_i)$ = Integral electron flux at E_i

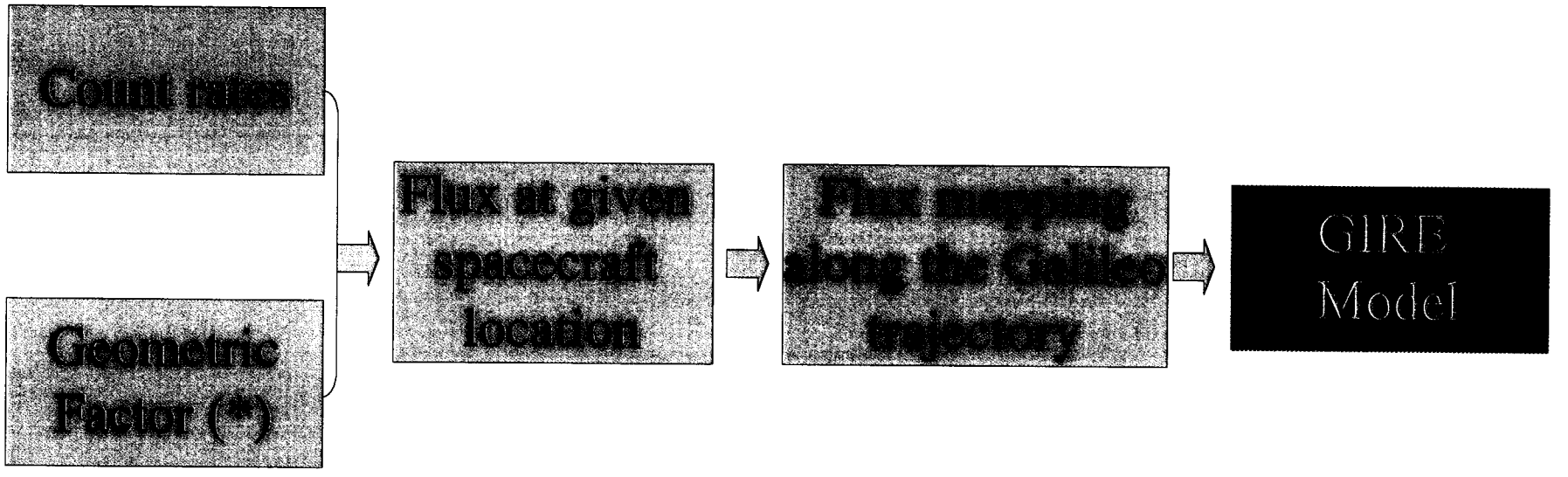
$\frac{dI(E_i)}{dE}$ = $J(E_i)$ = Differential electron flux at E_i

$J(E_i)$ = $J_0\,(E_i/E_0)^{-x}$ (units of $(cm^2\text{-}s\text{-}sr\text{-}MeV)^{-1}$)

$G(E_i)$ = Geometric factor at E_i

Galileo Interim Radiation Electron Model

SIMPLIFIED PROCESS



(*) EPD high energy channels were not completely calibrated at the time of the launch. Extensive Monte Carlo simulations were successfully performed to calibrate the instrument.

Galileo Interim Radiation Electron Model

In the third step, the geometric factors in combination with simplifying assumptions about the particle distribution functions were used to generate differential fluxes versus energy. Specifically, assuming that the electron particle flux spectra could be modeled over the 1 to 30 MeV energy range by a power law spectrum in energy, a method for inverting the count rates was devised that gave the electron fluxes versus energy. In addition, geometric factors for the lower energy EPD F1, F2, and F3 electron channels (0.174, 0.304, and 0.527 MeV respectively) were provided by T. Choo of JHU/APL that allowed the inclusion of lower energy fluxes. Finally, electron flux data from the Pioneer 10 and 11 spacecraft at 31 MeV were also included to extend the energy range of the model. Given flux estimates at 0.174, 0.304, 0.527, 1.5, 2.0, 11.0, and 31 MeV, a differential flux spectrum can be fit of the form:

$$F(E) = J_o E^{-A}(1+\frac{E}{E_o})^{-B} \qquad (1)$$

Where:

F =	Differential electron flux as a function of E
E =	Electron energy (MeV)
J_o =	Constant (roughly the differential flux at E = 1 MeV)
A =	Constant (approximately the power law index for the low energy component)
B =	Constant (A+B is approximately the power law index for the high energy component)
E_o=	Constant (approximately the breakpoint energy between low and high energy spectra)

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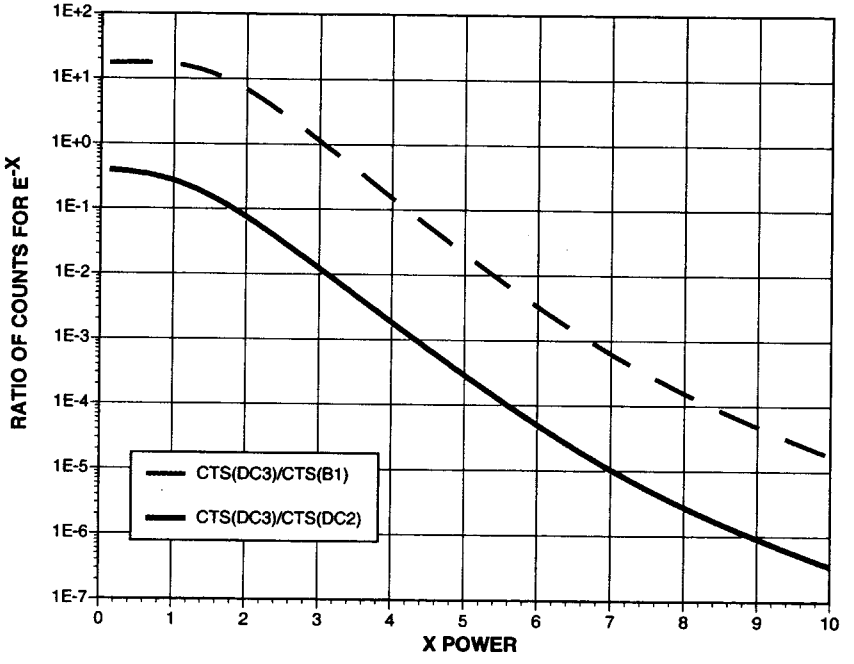
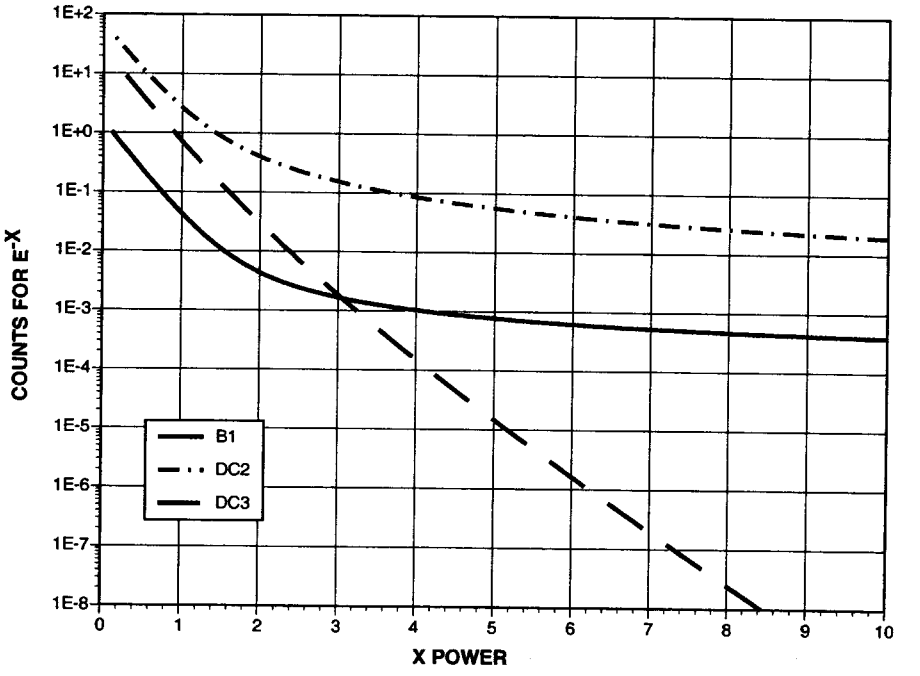
COUNT RATE TO FLUX CONVERSION

$$J(E) \sim J_0 (E/E_o)^{-X}$$



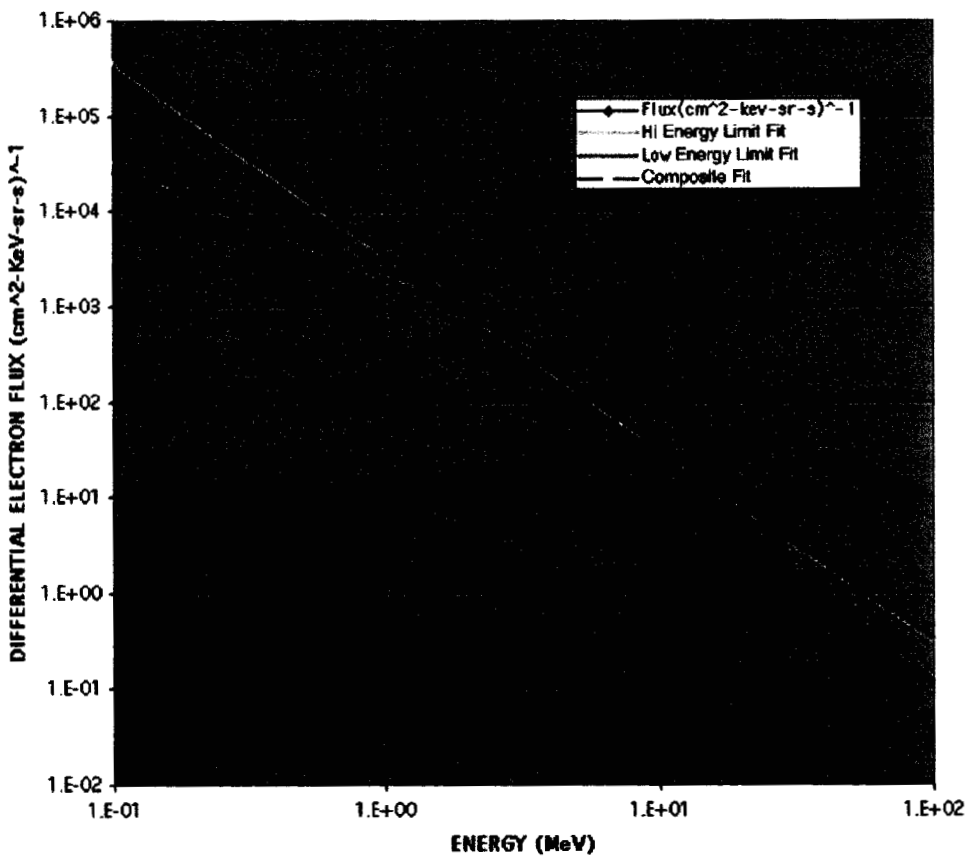


$$\frac{[\text{Cnts(DC3)/Cnts(B1)}]}{[\text{Cnts(DC3)/Cnts(DC2)}]} \text{ ---> } X$$

J_0 = [Obs Cnts]/[Pred Cnts from X]

Galileo Interim Radiation Electron Model

SPECTRAL FITTING PROCEDURE



$$F(E) = J_o E^{-A} (1 + \frac{E}{E_o})^{-B}$$

Where:

- **F = Differential electron flux as function of E**
- **E = Electron energy (MeV)**
- **J_o= Constant (roughly differential flux at E = 1 MeV)**
- **A = Constant (approximately power law index for low energy component)**
- **B = Constant (A+B is approximately power law index for high energy component)**
- **E_o= Constant (approximately breakpoint energy between low and high energy spectra)**

Galileo Interim Radiation Electron Model

For each of the seven energies, average fluxes were computed from the measurements falling in each spatial, radial interval of 0.5 L along the Galileo orbit between L-shells of 8 and 16. L is the distance, in Rj, from Jupiter's magnetic axis at which a given magnetic field line crosses the magnetic equator, the plane of which is slightly tilted with respect to the geographic equatorial plane. A spectrum of the form of Eq. 1 was fit to these averages for each L interval. For L-shell values in-between, the spectral components were interpolated. This is the base EPD omni-directional, equatorial model.

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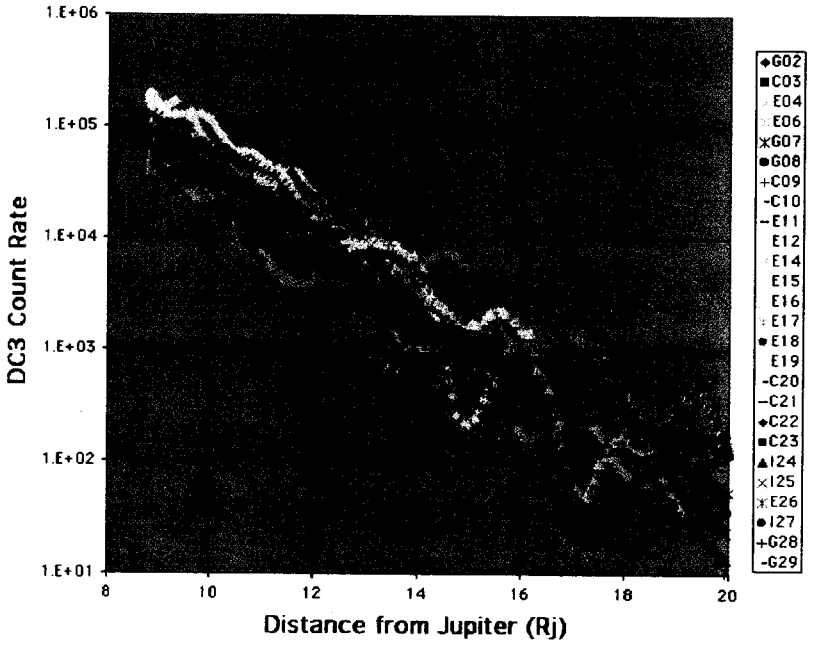
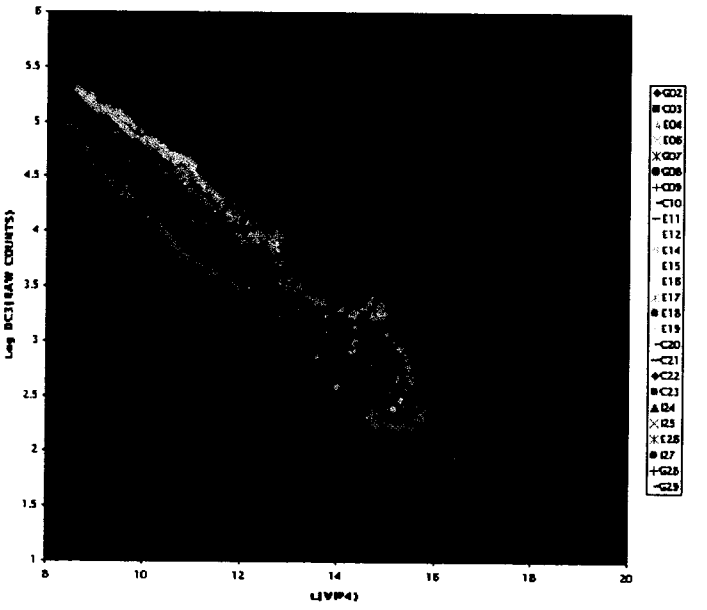
RADIAL VS L-SHELL ORBITAL VARIATIONS



DC3(11 MeV) Count Rates vs Rj
Orbits G02-G29



DC3(11 MeV) Count Rates vs L
Orbits G02-G29

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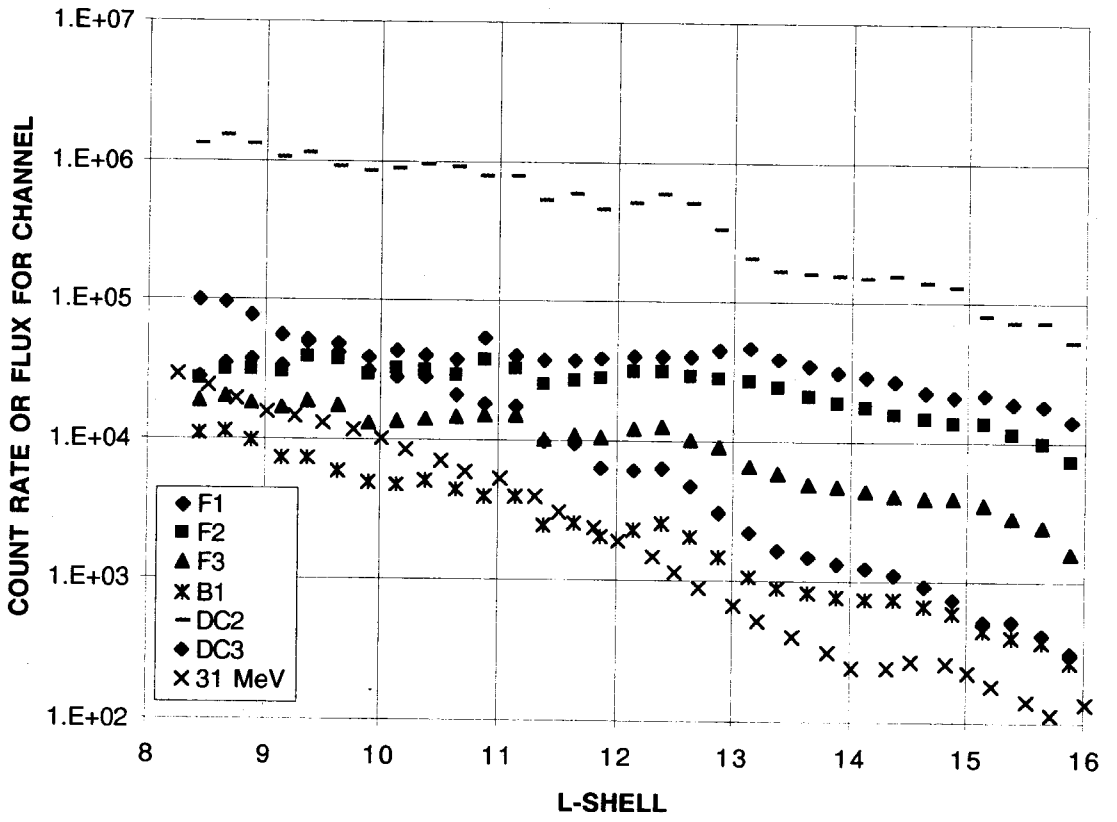
EPD COUNT RATE* AVERAGES VS L-SHELL



F1 = 0.174 MeV
F2 = 0.304 MeV
F3 = 0.527 MeV
B1 = 1.5 MeV
DC2 = 2.0 MeV
DC3 = 11.0 MeV
Pioneer = 31 MeV

*31 MeV Channel is Omni-Directional Flux

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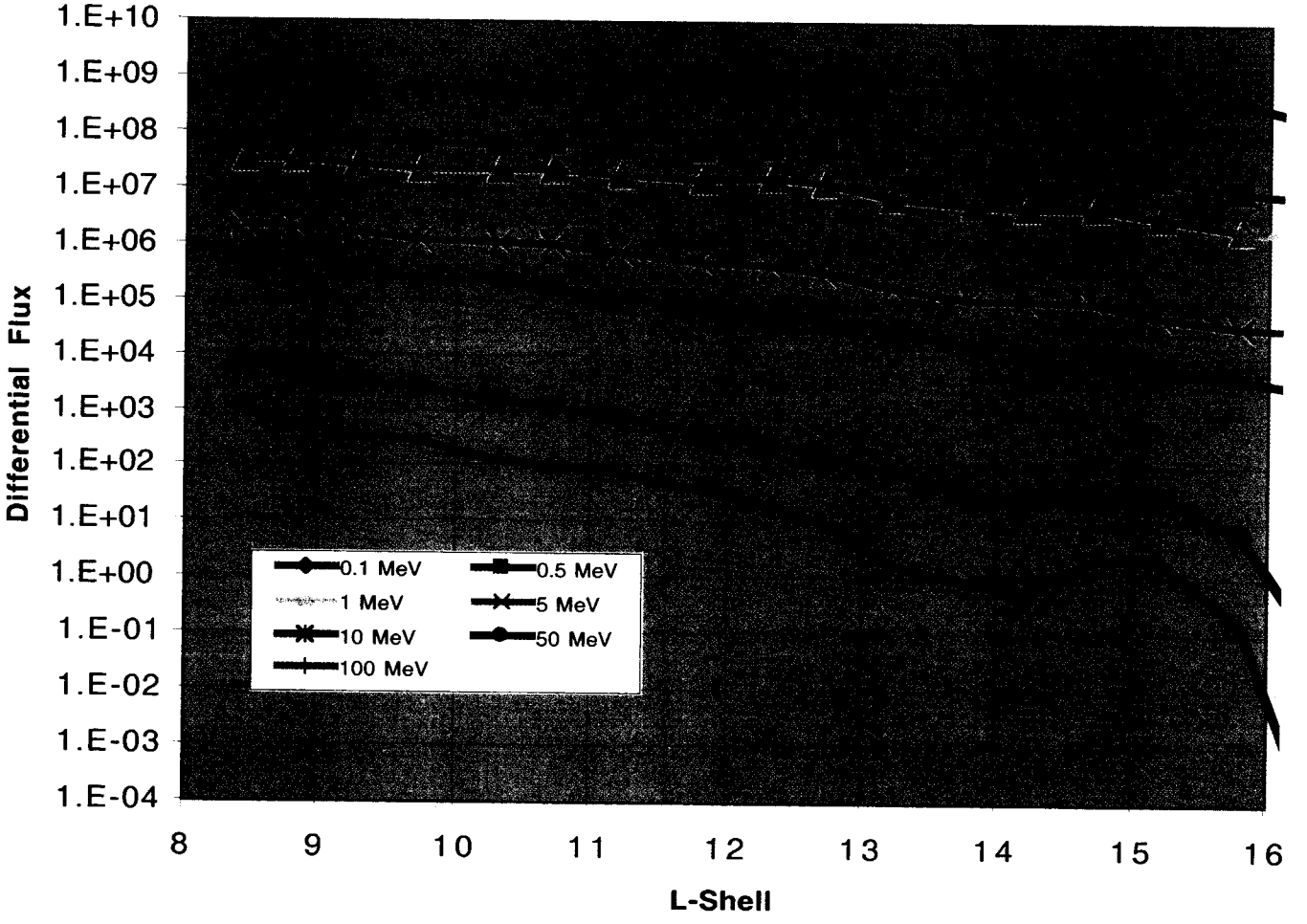
EPD OMNI-DIRECTIONAL ELECTRON MODEL FOR THE EQUATORIAL PLANE



*Units = $(cm^2\ s\ MeV)^{-1}$

Galileo Interim Radiation Electron Model

At this time, the EPD pitch angle data are still being analyzed. Pitch angle information (i.e., the particle flux relative to the magnetic field direction) is required to estimate fluxes at high latitudes. To provide this capability, the omni-directional equatorial model was next merged with the Divine radiation model pitch angle variations to provide complete latitude and L-shell coverage. This combination forms a complete model, the GIRE model, that can be used to provide updated radiation environment estimates. Unlike the original Divine model, which was based on single flybys by four spacecraft, the new GIRE model covers ~7 years of data and more than 30 orbits of Jupiter, providing a significant improvement in our knowledge of the variations in the jovian radiation environment.

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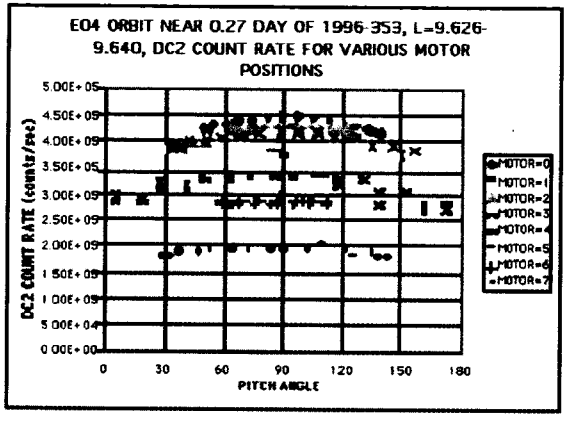
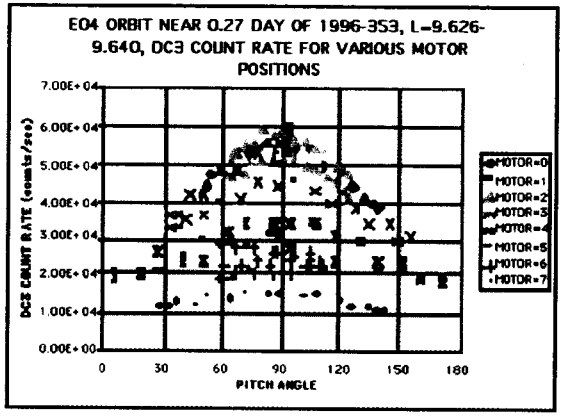
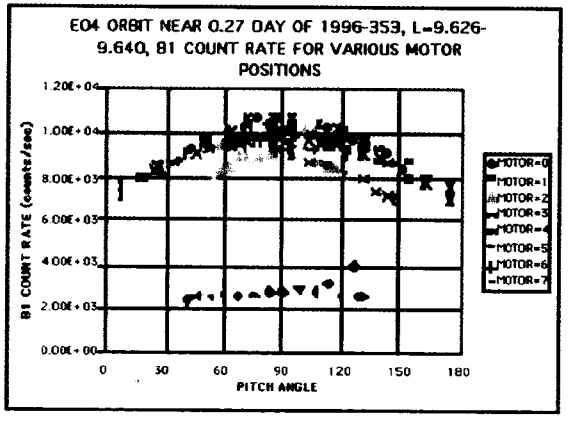
PITCH ANGLE DISTRIBUTIONS







REPRESENTATIVE EXAMPLES OF THE PITCH ANGLE DISTRIBUTIONS FOR B1, DC2, AND DC3 FOR THE PLAYBACK DATA

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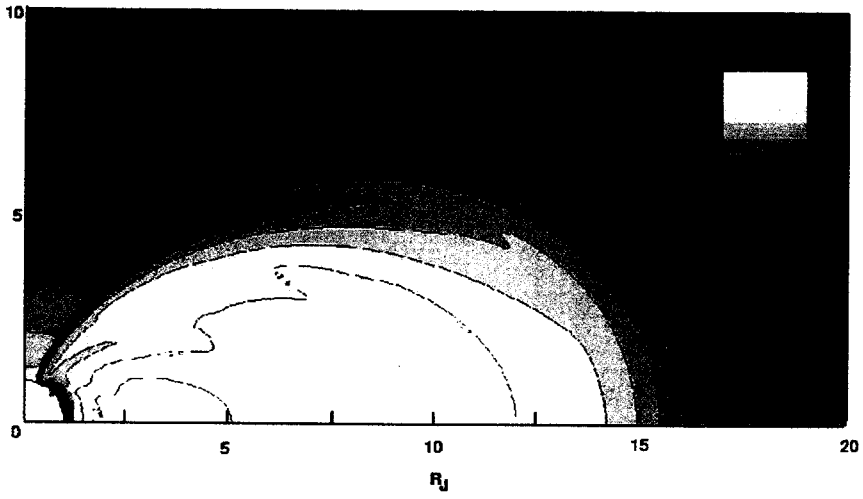
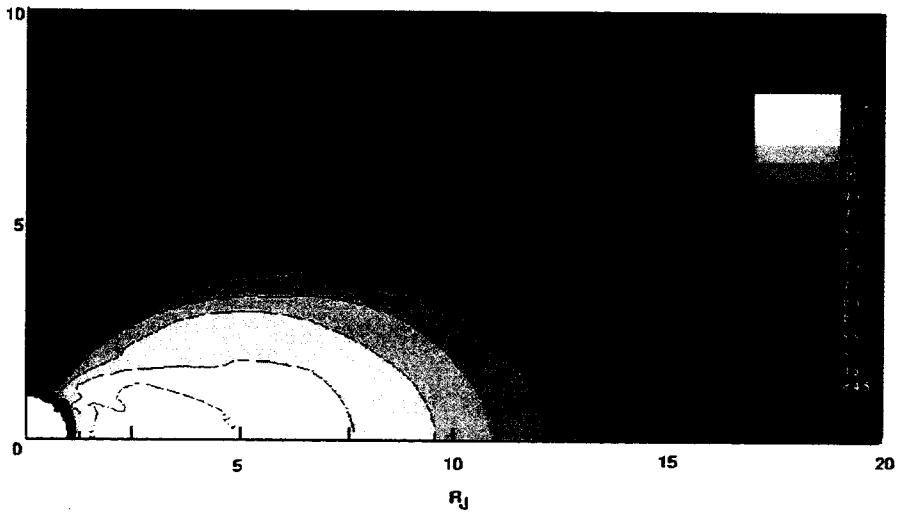
Divine Model Electron Fluences



Contour plot of the E>1 MeV high energy electron fluence (Log) at Jupiter as estimated from the Divine model. Fluences (cm^{-2}) are for a 10 hr period.

Contour plot of the E>10 MeV high energy electron fluence (Log) at Jupiter as estimated from the Divine model. Fluences (cm^{-2}) are for a 10 hr period.



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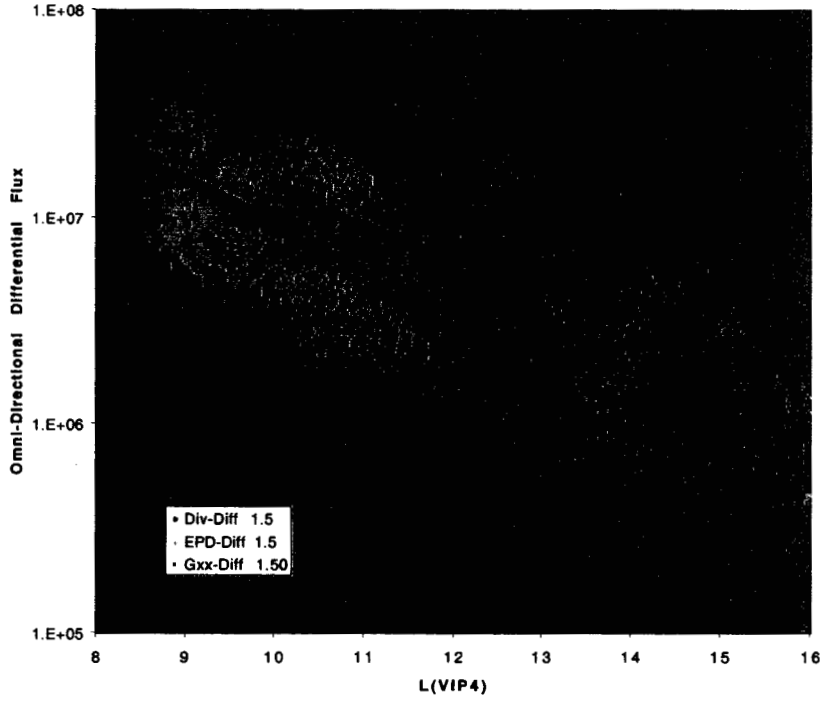
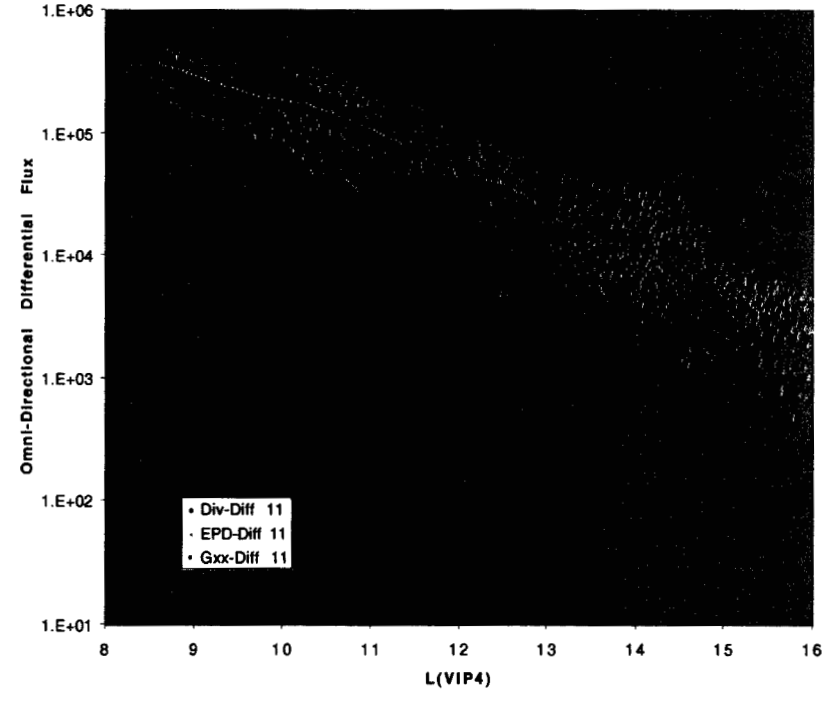
Divine Model Estimates vs GIRE Estimates



1.5 MeV ELECTRONS



11 MeV ELECTRONS

Blue = Divine; Pink = GIRE; Yellow = EPD Fits

Galileo Interim Radiation Electron Model

As a final step, the combined model was used to estimate the Europa mission dose/depth curve and compare it with the original Divine model estimates currently in use by the project. The prediction of the GIRE model is about a factor of 2 lower than the Divine model estimate over the range of 100 to 1000 mils (2.54 to 25.4 mm) of aluminum shielding, but exceeds the Divine model by about 50% for thicker shielding (where uncertainties in spectrum extrapolation make both models suspect). Again, these results tend to support the consistency of the Galileo model with previous spacecraft missions as represented by the Divine model. While work remains to be done in studying the unique variations in orbit C22, in completing the Galileo pitch angle analysis, and in reconciling remaining inconsistencies in the data, the GIRE model clearly represents a significant step forward in the study of the jovian radiation environment and is a useful and valuable tool for estimating that environment for future space missions.

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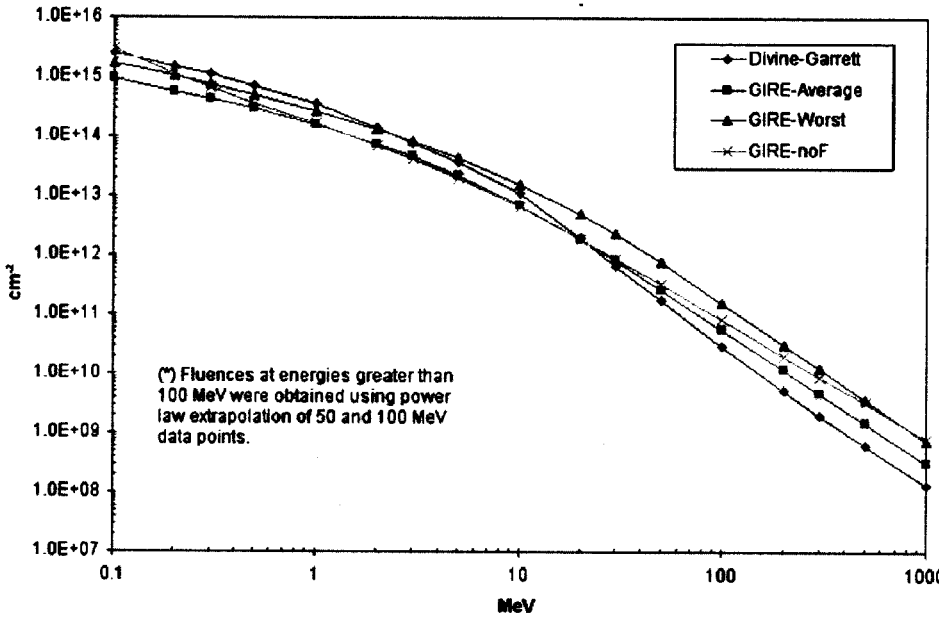
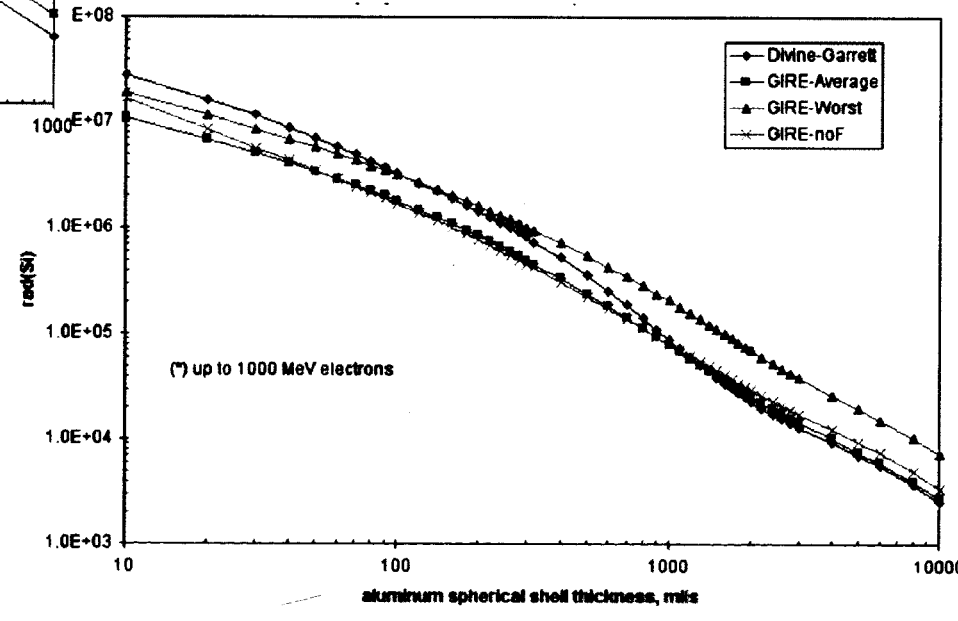
GIRE MODEL DOSE PREDICTIONS VS DIVINE MODEL FOR EUROPA MISSION



INTEGRAL ELECTRON FLUENCE



EUROPA MISSION DOSE

CONCLUSIONS

- APL EPD 1-11 MEV ELECTRON DATA CONVERTED INTO FLUX ESTIMATES USING MODELED GEOMETRIC CROSS SECTIONS
- AVERAGE FLUXES FOR L = 8-16 FIT WITH CONTINUOUS SPECTRUM FOR ENERGIES 0.174-31MEV (EPD OMNI-DIRECTIONAL EQUATORIAL MODEL)
- DIVINE MODEL PITCH ANGLE VARIATIONS COMBINED WITH EPD MODEL TO GIVE GIRE MODEL FOR L=8-16