The GIRE2 Model and Its Application to the Europa Mission

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Abstract—We present an empirical model of Jupiter’s electron radiation environment and its application to the design of the future NASA mission to Europa. The model is based on data from the Galileo spacecraft. Measurements of the high-energy, omni-directional electrons from the Energetic Particle Detector (EPD) and magnetic field from the Magnetometer (MAG) onboard Galileo are used for this purpose. Ten-minute averages of the EPD data are used to provide an omni-directional electron flux spectrum at 0.238, 0.416, 0.706, 1.5, 2.0, and 11.0 MeV. Additionally, data from the Geiger Tube Telescope onboard Pioneer 10 and 11 are used to calculate the flux of 31 MeV electrons. The Galileo Interim Radiation Electron model v.2 (GIRE2) combines these datasets with the original Divine model and synchrotron observations to estimate the trapped electron radiation environment. Unlike the original Divine model, which was based on flybys of the Voyager and Pioneer spacecraft, the new GIRE2 model covers about 7 years of data and more than 30 orbits around Jupiter from the Galileo spacecraft. The model represents a step forward in the study of the Jovian radiation environment and is a valuable tool to assist in the design of future missions to Jupiter. This paper gives an overview of GIRE2 and focuses on its application to the design of the future NASA mission to Europa. The spacecraft will orbit Jupiter and perform multiple flybys of the moon Europa, which is embedded in the middle of a very strong radiation environment. The radiation environment surrounding the moon as well as along the trajectory are described in the paper together with the implications of this environment on the design of a mission.

1. INTRODUCTION

The magnetosphere of Jupiter is one of the most extreme radiation environments in the solar system. Energetic particles trapped in the Jovian magnetic field form a belt-like configuration around the planet, which resembles the Van Allen radiation belts of Earth but is orders of magnitude more intense. Spacecraft intended to operate in this environment have to pay special attention to the selection of EEE parts, and the design of their shielding and grounding schemes. The flybys from the Pioneer 10 and 11 and Voyager 1 and 2 spacecraft as well as the 35 orbits from Galileo constitute most of the database of Jovian environment to date. Additionally, Juno is expected to get to the planet on July 4th, 2016 to study the poles and auroral regions that have never been sampled before with in-situ measurements. The heritage from these missions as well as the models of the radiation environment that they have enabled are key pieces of information for the design of the future NASA mission to Europa, which is expected to launch in the early 2020s.

The Jovian magnetosphere is dominated by the planet’s rotation rate, which is more than twice that of the Earth. The volcanos of Io eject sulfur and sulfur dioxide that climb hundreds of kilometers in height. Jupiter’s magnetosphere removes more than 10^7 kg/s of material from Io’s atmosphere and forms the so called Io torus, which is believed to be the main source of Jovian plasma. This cold plasma is accelerated outwards by the centrifugal force of the planet. At the same time, energetic particles are diffused inwards and form the intense radiation belts of Jupiter. The work by Divine and Garrett in 1983 [1] (D&G) was the first comprehensive study to put together a model of the radiation and plasma environment around Jupiter. The D&G model is an empirical model based on data from the Pioneers and Voyagers spacecraft, and has been the reference model for decades. In the second publication [2], the model was updated to include the latest data from Earth-based synchrotron observations. Another model is the Jovian Specification Environment Model (JOSE) [3] developed by ONERA in France. Compared to the D&G model, the JOSE model is based on the Salammbô theoretical code [4] in combination with data from the Energetic Particle Detector (EPD) of the Galileo spacecraft [5].

Galileo represents the main source of data for the Jovian environment. The spacecraft performed 35 orbits around the planet and measured the radiation environment along its...
orbit. In this paper we present the result of combining the measurements from the Galileo EPD with the D&G model, which we have named the Galileo Interim Radiation Environment model v.2 (GIRE2). GIRE2 addresses major weaknesses of the previous version of the model (GIRE) [6] like the limited spatial coverage (<16Rj) and the discontinuity at the boundary with the D&G model. Like its predecessor, GIRE2 is an empirical model developed at the Jet Propulsion Laboratory (JPL) and is an engineering tool developed to assist in the design of JPL’s Jovian missions. More specifically, the present paper provides a summary of the GIRE2 model and focuses on its application to the design of the Europa mission. The details of the implementation of the model will be described in a follow-on publication.

The following section provides a summary of the GIRE2 electron model. Section 3 focuses on the Jovian environment around the Europa moon and the application of the model to the design of a future NASA mission to Europa. The paper finishes with a summary and discussion of the findings.

2. The GIRE2 Electron Model

The GIRE2 electron model is based on data from the Voyagers, Pioneers, and Galileo spacecraft. More specifically, the GIRE2 model defaults to the D&G model for \( L \leq 8 \) (where \( L \), or \( L \)-shell, characterizes a specific magnetic field line and equals the distance in Jupiter radii along the magnetic equator between the center of the planet and the specified field line), and to an empirical model based on the Galileo EPD data outside of \( L > 8 \). Additionally, the Magnetometer (MAG) instrument onboard Galileo is used to determine the magnetic field at the location of the spacecraft, which is used to derive the \( L \)-shell corresponding to the measurements at that specific location. The different regions of the GIRE2 model are described below.

Each of the Pioneers and Voyagers spacecraft performed one Jupiter flyby, which are represented in Figure 1 and constitute the main source of data for the D&G model. The flybys from Voyager 1, 2 and from Pioneer 10 were mostly equatorial and the closest approach to Jupiter in the case of Pioneer 10 was \( \sim 3R_j \) from the center of the planet. Pioneer 11 explored a broader range of latitudes and got as close as \( 1.5R_j \). For the high-energy electron data, D&G used the measurements from the Geiger tube telescope (GTT), the trapped radiation detector (TRD), and the electron current detector (ECD) onboard Pioneers 10 and 11, and from the cosmic ray telescope (CRT) onboard Voyagers 1, and 2. Based on these data, D&G constructed a model that used 14 parameters and several equations to fit the flux of energetic electrons as a function of \( L \)-shell and pitch angle. Additionally, the D&G provides the distribution of the cold and warm plasma populations based on data from other Pioneer and Voyager instruments (not discussed here). The orbits described above allowed D&G to characterize the radiation environment very close to the planet as a function of pitch angle, which is the model used by GIRE2 inside \( L < 8 \).

Outside \( L > 8 \), the GIRE2 model is based on data from the Galileo spacecraft. More specifically, we use 10-minute data averages from the EPD provided by the Johns Hopkins University Applied Physics Laboratory (JHU/APL), which covered a range of 0.2-11 MeV in electron energy divided into 6 different channels (0.239, 0.416, 0.706, 1.5, 2.0, and 11.0 MeV). A seventh channel corresponding to 31 MeV electrons was incorporated using the data from the GTT onboard the Pioneers spacecraft. The measurements from the GTT were readily provided in flux units, while the EPD output was in count/s and had to be converted to flux. The study by Jun et al. [7] addressed this issue by performing three-dimensional Monte Carlo simulations to calculate the EPD geometric factors, which characterize the instrument response and are used to convert count rates into fluxes. The geometric factors from [7] were applied to the high-energy channels of the EPD data to build the GIRE2 model, while those for the low-energy channels (< 1 MeV) were directly provided by JHU/APL and represent the most up to date values.

![Figure 1 - Fly-bys of Pioneer 10 (P10), Pioneer 11 (P11), Voyager 1 (V1), Voyager 2 (V2), and the Galileo orbits (GLL)](image)

The GIRE2 model is additionally subdivided into two regions. These regions correspond to two different magnetic field topologies and are modeled differently. In the inner zone (\( L < 17 \)) the Jovian magnetic field resembles an offset tilted dipole. In this region we use the VIP4 magnetic field model [8], which was based in part on measurements from the Magnetometer (MAG) onboard Galileo, to express the location of the spacecraft as a function of \( L \)-shell. The radiation data in this region are fit as a function of this \( L \) parameter. In the outer zone (\( L > 17 \)), however, the magnetic field presents a sheet-like configuration and it is stretched into a magnetodisk. The magnetic field model of Khurana [9, 10,11] more accurately fits the Galileo magnetic field in this region of the Jovian magnetosphere, which adds an external
disk current to the internal magnetic field of Jupiter. Due to its distinct shape, the model of Khurana is parameterized as a function of radial distance to the planet and normal distance to the plasma sheet. The VIP4 and Khurana magnetic field models are presented in Figure 2, where it can be observed that they are mostly identical inside $L<17$ (in fact, the Khurana model uses the VIP4 parameters in the inner zone) but differ significantly in the outer region. The radiation model for the outer zone, therefore, uses the two parameters from the Khurana’s magnetic field model (radial distance to the planet and normal distance to the plasma sheet) to construct the fittings to the Galileo EPD data.

Figure 2 - Magnetic field line traces at 315° W longitude using the VIP4 (blue) and Khurana (red) models

For each of these regions, the geometric factors described above were used to convert counts to fluxes; this process assumed that the electron particle flux can be modeled to first order as a power law spectrum in energy. The flux data were next averaged over spatial regions. In the inner region, the (magnetic) equatorial crossings were identified, the data was fit in terms of $L$-shell along the magnetic equator, and we used the omni-directionality of the measurements to extend these fits to higher latitudes along the magnetic field lines. A double power law was used to fit the differential flux spectrum at each $L$-shell bin, which can be integrated in energy to give integral fluxes. In the outer region, the data was fit in terms of radial distance to the planet and normal distance to the plasma sheet, as specified by the Khurana magnetic field model, and a double power law was also used to fit the electron energy spectrum for each of these bins. A smoothing function was used to remove the discontinuity that appears between inner and outer zones at $L=17$ as well as the discontinuity between the D&G model and the inner zone at $L=8$. These result from the different coordinates used to parameterize the different regions of the model. The merged model is presented in Figure 3, which shows the $>1.5$ MeV electron integral flux as a function of equatorial distance from the center of the planet at a latitude of 110° W. The $>1.5$ MeV electron flux peaks at equatorial distances of <5R$_J$, but it is still high at the orbit of Europa ($\sim9.5R_J$) with an integral flux of $\sim3\cdot10^7$ cm$^{-2}$s$^{-1}$. As a comparison, the flux of $>1.5$ MeV electrons in the Earth magnetosphere peaks at ~4R$_E$ with a value of $\sim1\cdot10^6$ cm$^{-2}$s$^{-1}$ as given by the AE-9 mean model.

![Figure 3 - Integral flux of $>1.5$ MeV electrons given by the GIRE2 model at the equatorial plane and at 110° W longitude](image)

The GIRE2 model described above has been used to support the design and determine the environmental requirements of the most recent Jovian missions from the Jet Propulsion Laboratory like the Juno (on its way to Jupiter) or the Europa (under development) mission. In the next section we use the GIRE2 model to determine some of the key radiation parameters that impact the design of the Europa mission, which are currently being addressed in the Laboratory.

### 3. APPLICATION TO THE EUROPA MISSION

The Europa mission is a new NASA mission that was approved in June 2015 to continue to its formulation stage. The investigation is a joint effort between the Jet Propulsion Laboratory and the Applied Physics Laboratory that has the objective of studying the Galilean icy moon with the same name. The Europa moon is scientifically compelling because measurements from the Galileo spacecraft indicated that there may be an underlying water ocean underneath its icy crust, which may be capable of hosting microbial extraterrestrial life. The spacecraft will carry nine instruments from different institutions with the objective of confirming the existence and characterizing the ice shell and ocean of the moon, and studying their composition and geology.

The Europa mission will not directly orbit the moon but will perform 45 flybys (as conceived at the time of this paper) as it orbits Jupiter. The moon is immersed in the middle of a very strong radiation environment. This fact is illustrated in Figure 3 – note the high $>1.5$ MeV electron flux at the location of the moon ($R_J\sim9.5$). Additionally, Figure 4 shows the GIRE2 energy spectrum of high-energy electrons at $R_J\sim9.5$. The flux increases with decreasing energy following
a double power law function. The radiation exposure from an orbit around Europa would severely limit the survivability of the mission and led to the selection of the multi-flyby approach to limit the total dose.

The total ionizing dose (TID) is a parameter used to quantify the exposure to radiation and is a measure of the energy deposited by energetic electrons and protons in materials. The dose depends on the outside environment, the shielding material type and thickness, and the target material type and thickness. The first step to find the dose consists of calculating the fluence, \( f(E) \), of energetic particles reaching the spacecraft surfaces, where the fluence equals the integration of flux over time (along the trajectory) as a function of energy. The calculation of the dose involves both high-energy electrons and protons. For the case of electrons, the fluence is calculated using the GIRE2 model described above, while the calculation of the proton fluence is out of the scope of this paper and will be addressed in a future publication. The dose can then be expressed as follows

\[
D(E) = \frac{1}{\rho} \frac{dE}{dx} \bigg|_E f(E) \tag{1}
\]

where \( E \) is the energy and \( \rho \) is the density of the material. \( dE/dx \big|_E \) is typically called linear energy transfer (LET) and is a measure of the energy transferred to the material by an incident particle per unit distance of traversed material. The LET curves are tabulated for most materials and can be easily found in the literature. The total ionizing dose is obtained by integrating \( D(E) \) over energy

\[
TID = \int_{E_0}^{\infty} D(E) dE \tag{2}
\]

where \( E_0 \) is the smallest energy of the available spectrum. The TID is normally expressed in units of rads for a given material. SHIELDOSE [12] is a software capable of performing these calculations given the fluence as an input from GIRE2.

A preliminary estimation of the TID is commonly done using a reference shielding of 100 mils of aluminum. For this level of shielding, Figure 5 shows the cumulative TID along the Europa trajectory following the procedure described above and for this reference shielding. Each of the small steps in the figure corresponds to a peri- or apo-jove pass (close encounter with the moon), where the dose rate increases remarkably. The figure also clearly shows different mission phases or orbit changes; the one between April 2030 and December 2030 is especially benign in terms of radiation compared to the rest, which corresponds to the transition stage between the period of Europa anti-Jupiter hemisphere coverage and the period of Europa sub-Jupiter hemisphere coverage. Additionally, Figure 6 shows the magnetic field and integral flux of energetic >1 MeV and >10 MeV electrons during ten orbits in the Europa sub-Jupiter hemisphere coverage phase. It can be observed that both magnetic field and electron fluxes increase dramatically at specific times corresponding to moon encounters (orbit peri- and apo-joves), which reaffirms the importance of the multi-flyby approach to minimize radiation exposure.

The moon encounters are the times with the highest dose rate and contribute the most to the TID. The so called dose cap corresponds to the TID accumulated by the end of the mission. It the case of Europa, the dose cap for 100 mil of Al is ~3.0 Mrad as shown in Figure 5. For comparison, a 3-year mission in GEO sees no more than 100 krad behind 100 mil. The impact of the radiation environment on the Europa mission, therefore, is going to be significant even for this multi-flyby approach, which determines the selection of the parts, the design and thicknesses of the shielding, and limits the survivability of the spacecraft. Moreover, some components on the spacecraft that are sensitive to radiation exposure.

![Electron integral flux spectrum at 9.5R_J obtained with the GIRE2 model](image)

![Total dose along the Europa mission for a standard shielding of 100 mils of Al](image)
Figure 6 – (a) Magnetic field along the trajectory of the Europa mission. (b) >1 MeV and (c) > 10 MeV integral electron flux along the trajectory of the Europa mission obtained with the GIRE2 model.

are not going to be able to survive this dose level. Additionally, there is a requirement that says that radiation sensitive components have to be shielded to ensure that their TID exposure is no greater than 50% of their demonstrated tolerance (i.e., a radiation design factor (RDF) of 2 is required). This requirement is satisfied by building a heavily shielded box called a “vault” that hosts the most sensitive components. This is a common practice that was also employed to protect the sensitive parts of the Juno spacecraft [13]. In the case of the Europa spacecraft, the vault is ~400 mil thick aluminum. With this amount of shielding the dose inside the vault is reduced by more than one order of magnitude compared to the 3.0 Mrad dose cap and ensures that the components residing inside the vault will survive the extreme Jovian environment.

In addition to potential long term effects generated by TID, designers must also address internal electrostatic discharges (IESD), which can happen as a result of electron charges buried in dielectrics or on floating metals inside the spacecraft (internal charging). The orbits with the highest electron flux based on Galileo data were used to define the worst case environment in terms of IESD. Moreover, most of the electron deposition happens in a window of 40 hours around the perijove pass, which is taken as a representative period for triggering IESD. The risk of discharge, however, depends on the electron deposition rate as well as on the electron bleed off rate; it was determined that a resistivity of <10^{19} \, \Omega \cdot \text{cm} would bleed off the accumulated charge during the remaining part of the orbit. Based on this worst-case scenario, to account for temporal variation of the Jovian environment, a baseline environment for IESD was adopted that corresponds to 5 times the average given by GIRE2, which ensures that the chance of having a single orbit in the entire mission above this specification is less than 5%. In other words, 95 out of 100 missions will see no orbit that exceeds the defined baseline flux, which is in accordance with the mission accepted risk. The next step for the Europa radiation engineers is to develop requirements based on this threshold environment (5xGIRE2) that ensure the spacecraft is IESD safe. These requirements are derived in terms of maximum allowable dielectric area and thickness, maximum floating metal area and length, allowable coatings and paints, etc. [14], which will be determined from the results of tests, simulations, and analyses.

4. SUMMARY AND DISCUSSION

The Galileo Interim Radiation Electron model (GIRE2) is the new Jovian electron radiation environment model from the Jet Propulsion Laboratory. In this paper we have presented a summary of the model and used it to derive specifications for the future NASA mission to Europa. GIRE2 adds 10-minute average data from the Galileo spacecraft to its successor model by Divine and Garrett. The latter was based on flyby data from the Pioneers and Voyagers spacecraft and on Earth-based synchrotron observations. The GIRE2 model clearly distinguishes two different regions. In the inner zone (<17 Jupiter radii), Jupiter's magnetic field can be accurately represented using a tilted off-centered dipole, thus the electron fluxes in this region are parameterized as a function of L-shell. In the outer zone (17 to 50 Jupiter radii), however, the magnetic field is far from dipolar, and presents a sheet-like configuration instead; thus data are fit in terms of radial distance from Jupiter and the distance normal to the current sheet for the observation point. At every spatial bin, the data...
are additionally fit in energy using a double power law. In the present study we decided to focus on the engineering applications of the model. The detailed formulation as well as the specification of the proton environment will be addressed in a future publication. GIRE2 has been used here to evaluate the engineering implications of the electron radiation on the Europa mission. Due to the extreme radiation environment surrounding the Galilean moon as predicted by GIRE2, it was decided that the spacecraft would not directly orbit Europa but will carry out multiple-flybys instead from an orbit centered around Jupiter; this approach drastically reduces the radiation exposure of the spacecraft compared to a moon-centric orbit. Additionally, we calculated the total ionizing dose (TID) that the mission will experience throughout its lifetime and found that the dose cap for a standard 100 mils of Al shielding is ~3 Mrad. Some of the components on the spacecraft, however, will not be able to survive this dose. To address this concern, a heavily shielded box called the “vault” will be built as part of the spacecraft and will host the radiation sensitive components. The Europa vault is ~400 mil thick Al. This reduces the dose inside the box by more than one order of magnitude compared to the dose received by the rest of the spacecraft. Moreover, the vault ensures that the TID exposure of radiation sensitive components will be less than 50% of their demonstrated tolerance. Finally, we discussed the approach taken to address internal charging and electrostatic discharges (IESD) that may damage the components inside the spacecraft. An environment given by 5 times the average provided by GIRE2 is taken as a baseline for IESD purposes. This environment guarantees that the chance of having a single orbit outside of this specification is less than 5%, which lies within the risk tolerance accepted by the mission. For this baseline environment, the IESD requirements on components, assemblies, and subsystems will be defined based on the 40-hour fluence around the perijove pass. The charge accumulated on the spacecraft during this period is assumed to bleed off during the rest of the orbit provided that the resistivity is less than <10\(^{19}\) \(\Omega\) cm. The next step for the Europa mission’s radiation engineers consists of performing tests and analyses based on this worst-case environment specification, the results of which will be used to define the IESD requirements.

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**BIOGRAPHY**

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**Henry B. Garrett** was born on February 15, 1948 in San Francisco, CA. He was raised in Roswell, NM, graduating from Roswell Senior High School in 1966. He received a B.A. degree in physics (phi beta kappa, magna cum laude) in 1970 and M.S. and Ph.D. degrees in space physics and astronomy from Rice University in 1974. He subsequently spent 6 years in the US Air Force before joining the Jet Propulsion Laboratory, California Institute of Technology in 1980. He is currently a Principal Scientist in the Office of Safety and Mission Success. Dr. Garrett is a Member of AIAA, AGU, and AAS. He has published 4 books and has over 125 publications in the areas of space environments and their effects on space systems.

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**Insoo Jun** received a Ph.D. in Nuclear Engineering from UCLA in 1991. He joined to JPL’s Natural Space Environments Group in 2000 as a senior technical staff. He has been the group supervisor of the same group since 2014. Dr. Jun is also a Principal Scientist in the area of space radiation environment and shielding analysis/design. He has worked on almost all JPL flight projects including many mission studies for Jupiter/Europa exploration. Dr. Jun is a science team member of the following missions or mission studies: Mars Science Laboratory, Europa, Mars Odyssey High Energy Neutron Detector (HEND) instrument, Surface and Atmosphere Geochemical Explorer (SAGE), and Psyche. His professional experience includes the modeling of planetary and interplanetary space environments and in studying their impacts on spacecraft systems and components as well as interactions with bodies in the Solar System.

**Wousik Kim** received a Ph.D. degree in physical chemistry from UCLA in 1998 and M.S. and B.S. degrees in physical chemistry from Seoul National University, Seoul, Korea in 1991 and 1989, respectively. In 2007, he joined the Natural Space Environments Group of the Jet Propulsion Laboratory, California Institute of Technology, where he has been working on internal and surface charging of dielectrics and floating metals, requirement developments for missions, and assessment of natural and man-made space environment such as electron, proton, meteoroid, and orbital debris.

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