Nuclear Instruments and Methods in Physics Research B 269 (2011) 232–238

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

A deterministic electron, photon, proton and heavy ion transport suite for the study of the Jovian moon Europa

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ARTICLE INFO

Article history:
Received 15 October 2010
Received in revised form 3 December 2010
Available online 14 December 2010

Keywords:
CEPTRN
HZETRN
TID
Jupiter
Galileo
Europa

ABSTRACT

A Langley research center (LaRC) developed deterministic suite of radiation transport codes describing the propagation of electron, photon, proton and heavy ion in condensed media is used to simulate the exposure from the spectral distribution of the aforementioned particles in the Jovian radiation environment. Based on the measurements by the Galileo probe (1995–2003) heavy ion counter (HIC), the choice of trapped heavy ions is limited to carbon, oxygen and sulfur (COS). The deterministic particle transport suite consists of a coupled electron photon algorithm (CEPTRN) and a coupled light heavy ion algorithm (HZETRN). The primary purpose for the development of the transport suite is to provide a means to the spacecraft design community to rapidly perform numerous repetitive calculations essential for electron, photon, proton and heavy ion exposure assessment in a complex space structure. In this paper, the reference radiation environment of the Galilean satellite Europa is used as a representative boundary condition to show the capabilities of the transport suite. While the transport suite can directly access the output electron and proton spectra of the Jovian environment as generated by the jet propulsion laboratory (JPL) Galileo interim radiation electron (GIRE) model of 2003; for the sake of relevance to the upcoming Europa Jupiter system mission (EJSM), the JPL provided Europa mission fluence spectrum, is used to produce the corresponding depth dose curve in silicon behind a default aluminum shield of 100 mils ($\sim$0.7 g/cm^2). The transport suite can also accept a geometry describing ray traced thickness file from a computer aided design (CAD) package and calculate the total ionizing dose (TID) at a specific target point within the interior of the vehicle. In that regard, using a low fidelity CAD model of the Galileo probe generated by the authors, the transport suite was verified versus Monte Carlo (MC) simulation for orbits JOI–J35 of the Galileo probe extended mission. For the upcoming EJSM mission with an expected launch date of 2020, the transport suite is used to compute the depth dose profile for the traditional aluminum silicon as a standard shield target combination, as well as simulating the shielding response of a high charge number (Z) material such as tantalum (Ta). Finally, a shield optimization algorithm is discussed which can guide the instrument designers and fabrication personnel with the choice of graded-Z shield selection and analysis.

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1. Introduction

Due to the biological, geological and planetary science interest in the Jupiter icy moons Europa, Ganymede and Callisto, the Jovian system as a whole has been a target of robotic exploration since the early 1970s. This interest stems partly from observation and analysis of the Galileo probe (1995–2003) measurements, suggesting that the icy moons have liquid water ocean beneath their outer crust, with further spectral evidence for the existence of salt and organic materials on the surface. Of particular interest is the moon Europa which is identified as a high priority target in the decadal survey of solar system exploration [1,2].

The primary shield design constraint for a Jupiter mission is the planet's strong magnetic field, the strongest among the planets in the solar system. Its trapped particle environment is extremely higher in energy and flux density than the other planets, thereby greatly enhancing the intensity of its radiation belt. In the Jovian magnetosphere, the trapped particle environment includes

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0168-583X/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.nimb.2010.12.022

electron, proton, and carbon, oxygen and sulfur (COS) heavy ions. Reliable environmental predictive models for these trapped particles are essential to adequately shield robotic probes that will visit (flyby or captured) Jupiter in near future. Furthermore, these predictive models must also be able to explain fundamental physical phenomena associated with the Jovian trapped particle dynamics such as synchrotron radiation emission and polar region auroras.

Particle experiments onboard the Pioneers 10 and 11 and the Voyagers 1 and 2 probes, provided limited Jupiter flyby measured data. These measurements were used by Divine and Garrett of jet propulsion laboratory (JPL), to develop the first Jupiter trapped radiation environment model [3]. This model was used to establish a reference radiation effects design limit for the Galileo probe onboard electronics. During nearly eight years in the Jupiter magnetosphere, the Galileo probe made a number of major scientific discoveries while making 34 orbits around Jupiter. However, while the mission was a scientific success, the spacecraft was constantly beset with radiation induced anomalies from the planet's harsh radiation environment. Later, Garrett et al. [4] of JPL, using data from the Galileo energetic particle detector (EPD) instrument [5] which provided angular coverage and spectral measurements for electron, $Z \geqslant 1$ ions and elemental species helium through iron, developed an updated Galileo interim radiation environment (GIRE) model. The Galileo EPD provided a multifold increase in the temporal and spatial coverage of the Galilean trapped radiation environment as compared with the data that were used in the previous Divine model [3]. In 2010, a version of the GIRE model which accounted for the shadow effect of Europa ($R_E = 9.4 \times R_J$, $R_J = 71{,}400$ km), was utilized by JPL to generate a reference trapped electron and proton spectra for the upcoming Europa Jupiter system mission (EJSM) [6]. These spectra along with fitted spectra to the COS measured data by the Galileo probe heavy ion counter (HIC) instrument [7], were provided to the radiation community as reference trapped radiation environment definition for the EJSM mission.

In this paper, the JPL provided Europa reference spectrum, in conjunction with two high energy deterministic particle transport codes, namely, the coupled electron photon transport (CEPTRN) code and the high charge and energy transport (HZETRN) code, are used to compute the radiation exposure for a traditional aluminum silicon as a standard shield target combination. This exposure analysis is performed as judicious shielding strategies incorporated in the initial spacecraft design phase for the purpose of minimizing deleterious effects to onboard systems in the intense Jovian radiation environment, plays a major role in ensuring overall mission success. In addition, the advantages of using graded-Z materials using the shielding response of high charge number (Z) materials such as tantalum (Ta) is discussed. Finally, a shield optimization algorithm is used to guide the instrument designers and fabrication personnel with the choice of graded-Z shield selection and analysis.

The Jovian radiation environment will be presented first. A brief explanation of the particle transport formalism as implemented in the transport suite will follow. Verification result versus Monte Carlo (MC) simulation and validation result versus Galileo probe measurement will be shown next, followed by a simulation to show how shield designers can go about performing graded-Z analysis for the EJSM mission shield optimization.

2. Jovian radiation environment

The dominant trapped particle constituent at Jupiter environment is the high energy electron with E in the $0.1 \sim 1000$ MeV range. Jupiter is roughly 10 times larger than Earth in radius, while its magnetic moment is 10^5 times larger. At the equator the

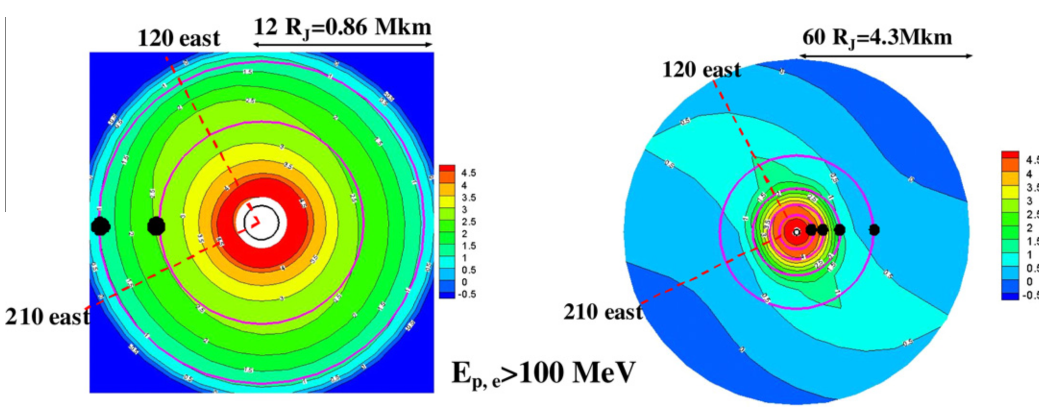

Fig. 1a. Jupiter trapped (GIRE 2003) equatorial plane proton (left) and electron (right) integral flux in unit of $\log_{10}(\text{cm}^2\text{-s})^{-1}$.

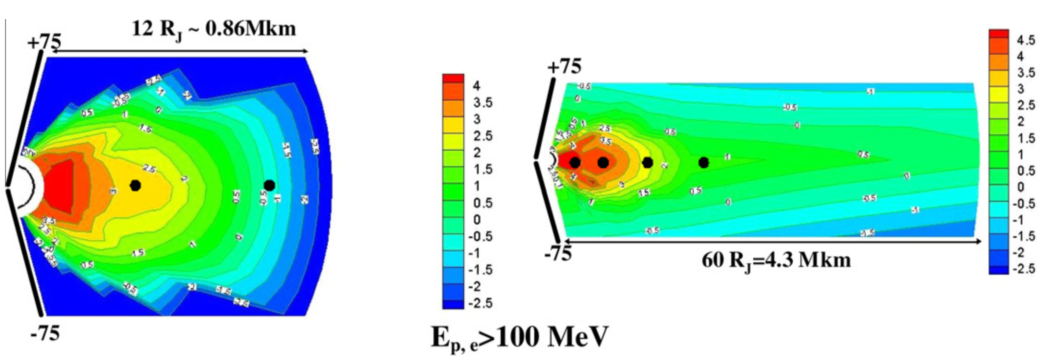

Fig. 1b. Jupiter trapped (GIRE 2003) longitudinal plane (120E) proton (left) and electron (right) integral flux in unit of $\log_{10}(\text{cm}^2\text{-s})^{-1}$.