Mitigating Deep Dielectric Charging Effects at the Orbits of Jovian Planets

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Abstract: Deep dielectric charging/discharging, caused by high energy electrons, is an important consideration in electronic devices used in space environments because it can lead to spacecraft anomalies and failures. The Jovian planets, including Saturn, Uranus, Neptune and Jupiter's moons, are believed to have robust electron radiation belts at relativistic energies. In particular, Jupiter is thought to have caused at least 42 internal electrostatic discharge events during the Voyager 1 flyby. With the development of deep space exploration, there is an increased focus on the deep dielectric charging effects in the orbits of Jovian planets. In this paper, GEANT4, a Monte Carlo toolkit, and radiation-induced conductivity (RIC) are used to calculate deep dielectric charging effects for Jovian planets. The results are compared with the criteria for preventing deep dielectric charging effects in Earth orbit. The findings show that effective criteria used in Earth orbit are not always appropriate for preventing deep dielectric charging effects in Jovian orbits. Generally, Io, Europa, Saturn ($R_S=6$), Uranus ($L=4.73$) and Ganymede missions should have a thicker shield or higher dielectric conductivity, while Neptune ($L=7.4$) and Callisto missions can have a thinner shield thickness or a lower dielectric conductivity. Moreover, dielectrics grounded with double metal layers and thinner dielectrics can also decrease the likelihood of discharges.

Key words: Jovian planets orbits; Earth orbits; deep dielectric charging effect; space radiation

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0 Introduction

Particle radiation creates a harmful environment in space that can lead to spacecraft anomalies. Sufficiently energetic electrons can penetrate the spacecraft structure, shielding, or instrument chassis and stop within cable insulation, circuit boards, and other dielectrics, depositing their charge. Electrons can be accumulated in dielectrics over the time due to the very low conductivity of the dielectrics. Once enough charge has been accumulated within a dielectric, arcing or discharge can occur if the resultant electric field strength exceeds the material's breakdown limit, dielectric strength. This phenomenon is known as the deep dielectric charging or internal electrostatic discharge (IESD)[1]. Deep dielectric charging can influence signal measurements and degrade dielectric properties, potentially causing satellite failure. According to the USA National Aeronautics and Space Administration (NASA), deep dielectric charging effects account for 25% of reported spacecraft anomalies and failures in the space environment [1]. At present, the deep charging effect is of concern because the process is not adequately understood. Hence, spacecraft designers are unable to apply appropriate protection methods[1]. Deep dielectric charging is mainly caused by high-energy electrons in space[2-15]. The Jovian planets, particularly, including Saturn, Uranus, Neptune, and Jupiter's moons, are thought to have robust electron radiation belts at relativistic energies[16-18].

Comparisons of the electron and proton radia-

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tion environments of Jupiter and Earth orbits are shown in Fig.1[19] and the electron radiation environment of Saturn's orbit is shown in Fig.2[20]. According to Figs. 1 and 2, Jupiter and Saturn's electron radiation belts show a shell distribution similar to Earth. In terms of spatial distribution, it is apparent that particle flux on the equatorial plane decreases with the distance. However, Jupiter and Saturn's electron radiation belts differ from Earth's because there is no obvious distinction between internal and external radiation belts. The high-energy electron flux of Jupiter and Saturn are higher as compared to Earth. In particular, Jupiter's orbit is 2—3 orders of magnitude higher. One important space environment effect directly related to these high-energy electrons is known as deep dielectric charging. Jupiter is believed to have caused at least 42 internal electrostatic discharge events during the Voyager 1 flyby, and the Jupiter Galileo Orbiter also experienced some equipment anomalies for which internal electrostatic discharge is the most likely cause[21-24]. Measurements of energetic electrons in the Galileo orbiter in Jupiter's magnetosphere show that Jupiter's moons Io, Europa, Ganymede, and Callisto also have high-energy electron fluxes[24]. Hence, the deep dielectric charging effects of these moons' orbits also require the consideration.

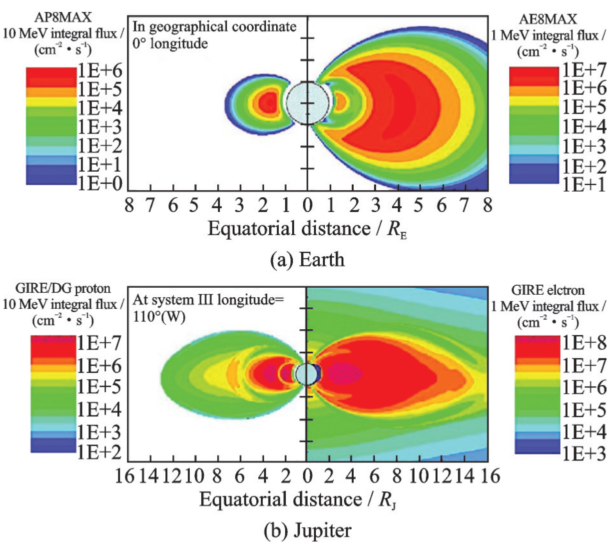

Fig.1 Comparison of the electron and proton radiation environments of Jupiter and Earth orbits[19]

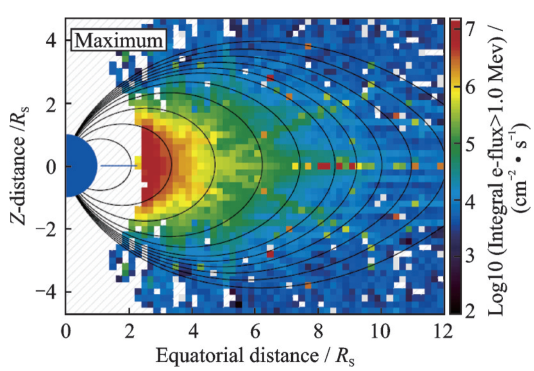

Fig.2 Electron radiation environment above 1 MeV in Saturn's orbit[20]

The ice giants Uranus and Neptune are the least understood class of planets in our solar system. However, they are the most frequently observed type of exoplanet. Uranus and Neptune are fundamentally different from the better-explored gas giants, Jupiter and Saturn[18]. The physical and atmospheric properties of Uranus and Neptune remain poorly constrained and their roles in the evolution of the Solar System are not well understood[18]. Therefore, the exploration of an ice giant system is a high priority science objective as these systems challenge our understanding of planetary formation and evolution. Uranus and Neptune orbits also have robust electron radiation belts at relativistic energies[18]. Fig. 3 shows the omni directional flux map of Uranus in polar R-A coordinates for electrons above 1 MeV[25] and Fig.4 shows spectrograms of energetic ions and electrons from Voyager 2 LECP[26]. In Fig. 4, the BS, magnetopause MP, and Triton (Tr) orbit crossing times are shown on top and radial distance in units of planetary radii (1 RN = 24 765 km) are noted in the middle. Similar to

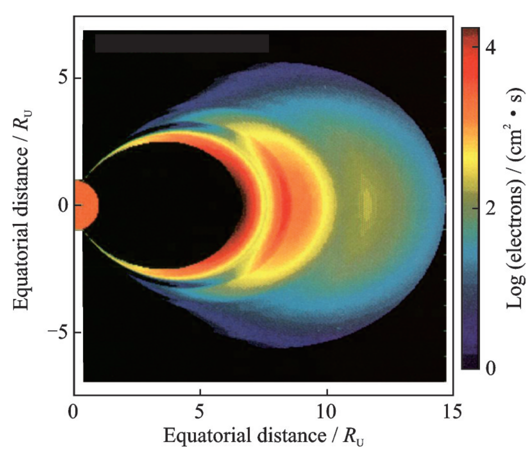

Fig.3 Omnidirectional flux map of Uranus in polar R-A coordinates for electrons above 1 MeV[25]

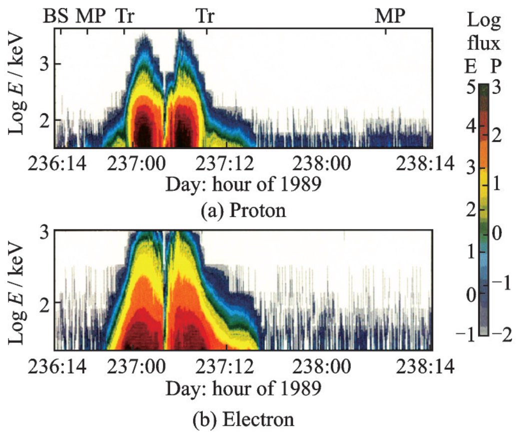

Fig.4 Spectrograms of energetic ions and electrons from the Voyager 2 LECP[26]

Earth's radiation belt, those of Uranus and Neptune display a shell distribution. However, the Uranus' electron radiation belt demonstrates an obvious distinction between the internal and external radiation belts, while the Neptune's does not. The electron flux of Uranus and Neptune are lower as compared to Earth's radiation belt.

In the past decades, many spacecraft have arrived in the Jovian system, including Galileo, Pioneer 10/11, Voyager 1/2, Ulysses, Cassini, and New Horizon. Juno has been orbiting Jupiter for several years and brought new discoveries of Jovian system[27-28]. The exploration of Jovian planets is a hotspot for future deep space exploration. A NASA planned mission Europa Clipper will launch to explore the fourth largest moon of Jupiter, Europa, to investigate its habitability, no earlier than 2022[29]. An ESA planned mission, JUICE, will launch to explore Ganymede and characterize the Jupiter system no earlier than 2025[30]. China also has a plan to visit the Jovian system for the first time[31]. In line with this, increasing attention has been paid to the deep dielectric charging effects in the orbits of Jovian planets[19,32]. Jovian planets have a different high-energy electron radiation environment from Earth. Therefore, criteria that are effective for preventing deep dielectric charging in Earth orbit are not necessarily suitable for Jovian planets, and effective design rules for these planets need to be developed. Current research on Jovian planets is primarily focused on the space radiation environment. Particle models for Jovian planet electron radiation belts have been established. Deep dielectric charging for Earth orbits has been studied for decades. There are guidelines, such as NASA-HDBK-4002A, to mitigate the charging effects[2]. Several evaluation tools for engineering, such as NUMIT and DICTAT[15,33], have also been developed. Recently, some research has been done on the deep dielectric charging for Jupiter missions. The DICTAT code was modified to extend the validity of the code to higher electron energies and high atomic number materials[34]. Simulations using the modified code indicate that the Jovian environment is more severe in terms of internal charging than the terrestrial geostationary environment and that shielding mass can be saved by using tantalum instead of aluminum. To estimate the charging environment and its effects at Jupiter for the Juno mission and the Europa orbiter, Garrett et al.[35] used the Divine radiation models to estimate the Jovian charging effects. They showed that standard charging mitigation techniques cannot prevent them from being a problem. Wang et al.[31] have evaluated the total ionizing dose (TID) and internal charging effect around Jupiter. In internal charging evaluations, a worst-case electron environment with 99% percentile from the JOSE model and a certain orbit with high inclination or eccentricity in a Jupiter-orbiting mission is chosen, and the shielding properties of high-Z tantalum and low-Z aluminum are studied. Results show that the former is a better choice of shielding material than the latter for a Jupiter mission.

At present, many internal charging software, such as DICTAT, are developed for Earth orbit. Most of these software use Weber's range equation to simulate the interaction between electron and material. The energy limit of the Weber range formula (10 MeV) covers the energies encountered throughout terrestrial space because the current provided by electrons above about 5 MeV is negligibly small[36]. However, for Jupiter orbits, there are significant numbers of electrons at energies up to 10 MeV. In this paper, the GEANT4-RIC (radiation-induced conductivity) method is used. GEANT4, developed for high energy physics, can simulate the transport and deposition processes of all possible energy particles. Therefore, GEANT4-RIC is suitable for Jovian planets' orbits.

1 Reresearch Methods and Electron Spectra

The deep dielectric charging effect is related to the electron environment, dielectric characteristics, and shield thickness. Different materials with the same thickness have different shielding effects. Shield effects are also measured using aluminum equivalents because it is so widely used as a shield material in spacecraft. The shield thickness of Al (Aluminum) is also used in simulations. In this paper, GEANT4, a Monte Carlo toolkit, and RIC are used to simulate the deep dielectric charging effects of Jovian planets. This method is referred to as GEANT4-RIC (Fig.5).

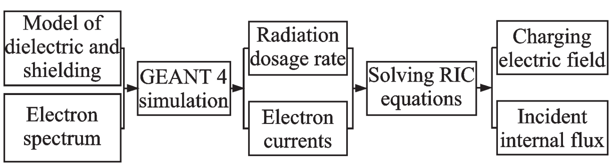

Fig.5 Schematic diagram of the deep dielectric charging effect simulation

The RIC model is as follows[37-38]

$$\varepsilon \frac{\partial E(x,t)}{\partial x} = \rho_f + \rho_t(x,t) \tag{1}$$

$$\sigma_d E(x,t) + \sigma_r(x,t)E(x,t) + J_e(x,t) + \varepsilon \frac{\partial E(x,t)}{\partial t} = J_0(x,t) \tag{2}$$

$$\frac{\partial \rho_t(x,t)}{\partial t} = \frac{\rho_f}{\tau}\left(1 - \frac{\rho_t(x,t)}{\rho_m}\right) \tag{3}$$

$$V(x,t) = -\int_0^x E(x,t)\mathrm{d}x \tag{4}$$

$$\sigma_r(x,t) = k\dot{D}(x,t)^{\Delta} \tag{5}$$

$$\dot{D}(x,t) = 1.6\times 10^{-11}\times \frac{W_d(x,t)}{T_s \rho A_m \Delta x} \tag{6}$$

$$J_e(x,t) = -\frac{N(x,t)e}{T_s A_m} \tag{7}$$

where x is the depth of dielectric, t the charging time, ε the dielectric constant, ρ_f the free charge density, σ_d the dark conductivity, τ the trap time constant of free charges, ρ_m the maximum trap charge density, E the electric field, ρ_t the trap charge density, J_0 the total current, V the electric potential, k and Δ constants, ρ the density of the dielectric, A_m the area of the dielectric, e the elementary charge, Δx the thickness of each layer, T_s the simulation time, W_d the energy deposited in each layer, and N the number of electrons passing through each layer. W_d and N can be obtained by the GEANT4 toolkit.

Eqs (1), (2), and (3) are the Poisson, current continuity, and charge trap equations, respectively. Eq.(4) relates the electric field and potential. Eq.(5) presents the calculation for RIC σ_r. Eq.(6) calculates the radiation dose rate $\dot{D}$. Eq.(7) calculates the incident electron current J_e.

Simulation inputs are the electron environment and the dielectric and shielding model. Outputs include the incident internal flux and deep dielectric charging electric field. The electric field, which is strongly related with incident internal flux, is the fundamental discharge cause. The GEANT4 geometry and tracking class can trace and record the electron history as tracks. Hence, the charge and energy deposition within an area of concern area can be obtained using statistical analysis of these tracks. Further details on the analytical method used can be found in Refs.[37-38]. The electrical properties of materials have a relationship with the temperature. However, the deep dielectric charging usually occurs in the interior of the spacecraft. The temperature inside the spacecraft is controlled to around room temperature generally. The influence of temperature is not significant for most equipments inside.

Electron spectra for the orbits of Earth and Jovian planets, including Io, Saturn, Uranus, Neptune, Europa, Ganymede, and Callisto, are chosen as inputs. These spectra, which decay exponentially in space, are shown in Fig.6. High energy electrons (up to 1 GeV) of the Jovian planets orbit and Earth orbit account for a small fraction of the total electron flux, which can cause less deep dielectric charging on the spacecraft in those orbits. The electron flux is always changing along the orbit, and the deep dielectric charging is a dynamic process. One should discuss the dynamics of the electron flux. However,

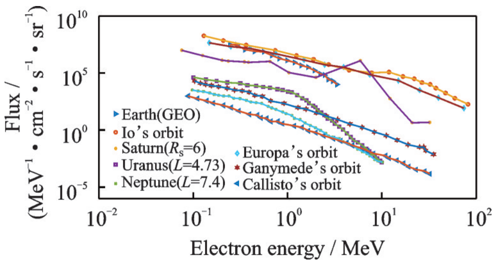

Fig.6 Electron spectra for orbits of Jovian planets[1,16,18,24,32,34]

the static electron flux and equilibriums condition also have significance in practice, because the deep dielectric charging anomalies mostly occur when the high electron flux exists for a long period which exceeds the charge constants[38].

The electron spectrum of Earth (Geostationary Earth orbit (GEO)) is from NASA-HDBK-4002A[1]. The electron spectrum of Io's orbit was obtained from the Galileo Interim Radiation Electron Version 2 (GIRE2) model for $R_J = 6$ and it was assumed that particles are isotropic[16]. Although there is little difference between the low energy electron fluxes of the orbits of Earth (GEO) and Io, the high-energy electron flux of Io's orbit is greater than that of Earth. The electron spectrum in the Saturn (R_S=6) orbit is mainly derived from Cassini LEMMS and CAPS measurements and also includes high energy electron measurements from Pioneer 11 and Voyager 2[34]. During the analysis of the Cassini data, strong dynamics were observed in the measurements. Hence, the used electron spectrum is the maximum possible electron spectrum. We selected the maximum flux of each energy point. The maximum flux at 6 MeV may be caused by the dynamic change of high energy electron flux. To respect the facts, we did not smooth the electron spectrum. The selected Uranus electron spectra has the most intense 1 MeV fluxes observed at Uranus by Voyager spacecraft at L=4.73[18]. The Neptune electron spectra was sampled by Voyager 2 near L=7.4 at the peak of about 1 MeV rate profile[18]. The electron spectrums of Europa are from the latest radiation belt models developed by JPL for the outer planets[39]. The electron spectrums of Ganymede and Callisto are from the Galileo Orbiter and the model spectrum (DG-83) of Divine and Garrett[24]. As shown in Fig.6, Io's orbit has the worst electron environment, at a high energy electron of up to several MeV.

2 Results

2.1 Incident internal flux versus shielding thickness

According to NASA-HDBK-4002A, to eliminate the risk of deep dielectric charging in GEO, approximately 2.8 mm (110 mils) of an aluminum equivalent (hereafter Al equivalent) is recommended[2]. Experience and observations from the CRRES (Combined release and radiation effects satellite) and others have shown that if the normally incident internal flux is less than 0.1 pA/cm^2, there are few, if any, deep dielectric charging problems[2]. The approximation of 0.1 pA/cm^2 as a nominal threshold for deep dielectric charging is empirically based, not physically based, and thus has limits[2]. Moreover, Bodeau and Balcewicz recommend 0.01 pA/cm^2 as the safety flux[2,40-41].

The shielding layer can block electrons under certain energies from entering the spacecraft. The incident internal flux decreases as the thickness of the shielding layer increases. Fig.7 shows the relationship between the incident internal fluxes and the Al equivalent shielding thickness. The safety shield thickness line of 2.8 mm Al equivalent for GEO and safety flux lines of 0.1 pA/cm^2 and 0.01 pA/cm^2 are also indicated. It is apparent that, for the same shield thicknesses, the Io orbit has the biggest incident internal flux. For the GEO safety shield thicknesses line of 2.8 mm Al equivalent, the incident internal fluxes for the orbits of Io, Europa, and Saturn (R_S=6) orbits are greater than 0.1 pA/cm^2. For Uranus (L=4.73) and Ganymede, it is between 0.1 pA/cm^2 and 0.01 pA/cm^2. While for the orbits of Earth (GEO), Neptune (L=7.4) and Callisto, it is less than 0.01 pA/cm^2. Generally speaking, missions to Io, Europa, Saturn (R_S=6), Uranus (L=4.73), and Ganymede should have a thicker shield or a higher dielectric conductivity, while those to Neptune (L=7.4) and Callisto can have thinner shields or a lower dielectric conductivity.

The incident internal flux of the Io orbit is approximately 96.41 pA/cm^2 under 2.8 mm of Al equivalent, much higher than the safety internal flux of 0.01 pA/cm^2. As shown in Fig. 7, to achieve a safety internal flux of less than 0.01 pA/cm^2, a shielding thickness of at least 268.5 mm of Al equivalent is required, about 100 times thicker as compared to GEO. The incident internal flux of Saturn (R_S=6) orbit, Europa orbit, Ganymede orbit and Uranus orbit (L=4.73) are approximately 14.59, 3.59, 0.09, and 0.07 pA/cm^2, respectively, which are under 2.8 mm of Al equivalent and higher than the safety internal flux of 0.01 pA/cm^2. However, the incident internal flux of the GEO orbit, Neptune (L=7.4) orbit, and Callisto orbit are lower than the safety internal flux of 0.01 pA/cm^2 and under 2.8 mm of Al equivalent. Therefore, effective criteria for preventing the deep dielectric charging effects in GEO are not appropriate for Jovian orbits.

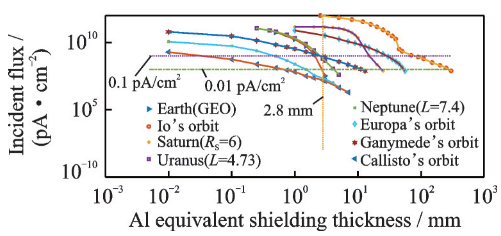

Fig.7 Relationship between the incident internal flux and Al equivalent shielding thickness in Jovian orbits

Table 1 provides the safety shield thicknesses at Jovian orbits following both the 0.1 pA/cm^2 and 0.01 pA/cm^2 standards. Deep dielectric charging does not appear to be an issue in Callisto orbit because spacecraft generally have shield thicknesses greater than 0.7 mm of Al equivalent, which can block the incident internal flux to a safety level of 0.01 pA/cm^2. For the Neptune (L=7.4) and Uranus (L=4.73) orbits, the shield thickness should be at least 1.5 mm and 4.3 mm of Al equivalent to achieve a safety level of 0.01 pA/cm^2, while Ganymede, Saturn (R_S=6), Europa, and Io missions should have shielding thicknesses of 11.0, 23.3, 53.6 and 268.5 mm Al equivalent, respectively.

Table 1 Required safety shield thicknesses in Jovian orbits mm

Orbit	Standard	
	0.1 pA/cm^2	0.01 pA/cm^2
Earth(GEO)	2.1	2.7
Io orbit	77.1	268.5
Saturn (R_S=6)	15.5	23.3
Uranus (L=4.73)	2.5	4.3
Neptune (L=7.4)	0.5	1.5
Europa orbit	29.2	53.6
Ganymede orbit	2.1	11.0
Callisto orbit	$<$0.1	0.7

The space radiation in the Jovian orbits can also have other major effects such as the total ionizing dose effect. Therefore, appropriate protection methods would be those that address these other space radiation effects as well. Jun et al.[42] presented a comparison between the total ionizing dose-depth curves of the GEO and Europa orbits. The comparison results show that for a total ionizing dose of around 1 e^2 rad/day (which is the result under 2.8 mm of Al equivalent in GEO), approximately 200 mm of Al equivalent is required for the Europa orbit. A shielding thickness of 53.6 mm of Al equivalent, which is suitable for deep dielectric charging, in not enough for the total ionizing dose effects in the Europa orbit. Therefore, in this case, the dielectric charging effect is not an important consideration when choosing the shield thickness.

According to Ohm's law ($J=\sigma E$), the electric field is determined by current and conductivity, including dark conductivity and radiation-induced conductivity (RIC). Therefore, to avoid deep dielectric charging effects in Jovian orbit, it is possible to use a dielectric with a higher conductivity compared to the dielectric used in Earth orbit.

Io is of great scientific interest since it was first in situ surveyed by the Pioneer spacecraft[43]. Io is the most volcanically active planetary body. Io orbits within Jupiter's intense magnetic field, which means Io constantly couples with Jupiter's magnetosphere. The role of Io and Jupiter in their mutual interaction and the nature of their coupling were elaborated by the two Voyagers flybys in 1979, and subsequent exploration of this system by the Galileo orbiter mission has improved our understanding. However, Io is also the innermost among Jupiter's moons (Europa, Ganymede, and Callisto are the others in order of distance from Jupiter) and thus has the worst electron environment. Wherefore, Io orbit is selected as the research target.

Different dielectrics should have different shielding layers. The study will further analyze FR4 (glass reinforced epoxy laminate) and PTFE (polytetrafluoroethylene) dielectric in Io orbit. FR4 and PTFE are widely used in satellites and are among the components most seriously affected by the deep dielectric charging effect[1-2]. Experiments both onboard spacecraft and in ground-based laboratories have shown that electric fields are the fundamental cause of electrostatic discharge[7]. The methods used to analyze FR4 and PTFE, and their physical characteristics, can be found in Refs.[37-38].

2.2 Maximum saturation electric field versus shield thickness

Deep dielectric charging appears to rise approximately exponentially, gradually reaching saturation. This saturated electric field is at a maximum prior to discharge[5]. Furthermore, the charging electric field also varies across the dielectric and the maximum value is at different positions according the type of grounding. Dielectric grounding types include front with ground, back with ground, and double with ground. The maximum values for the front, back and double layers with ground are near the back, front and middle of of the dielectric, respectively. The charging risk is determined by the maximum charging electric field. Therefore, the maximum saturation charging electric field can be used as an evaluation index[38].

NASA-HDBK-4002A shows that the dielectrics of most common, good-quality spacecraft may break down when their internal electric fields exceed 2×10^7 V/m, which suggests that the internal electric field should be less than 4×10^6 V/m to avoid internal dielectric discharging[1]. For this study, we considered 2×10^7 V/m as the breakdown threshold and 4×10^6 V/m as the safety threshold for internal electric fields.

The maximum saturation charging electric field under different shield thicknesses are calculated and shown in Fig.8. The maximum saturation charging electric field decreases as shield thickness increases. With increases in shield thickness, the number of electrons that can penetrate the shielding layer and deposit in the dielectric decreases, so the electric field in the dielectric decreases. The thickness of the dielectric in the simulation is 1.6 mm, which is typical of the FR4-PCB thickness used in satellites. The threshold electric field lines of 2×10^7 V/m and 4×10^6 V/m are also indicated in Fig.8. Following 2×10^7 V/m as the break down threshold and 4×10^6 V/m as the safety threshold for internal electric fields, the shield thickness of front with grounding (GND) should be at least 38.9 mm and 30.8 mm of Al equivalent. The shield thickness of the back with GND should be at least 39.4 mm and 30.5 mm of Al equivalent. The shield thickness of double GND should be at least 37.3 mm and 25.6 mm of Al equivalent. Ground types significantly affect the charging electric field, and grounding with double metal layers can significantly decrease the charging electric field and thus decrease the risk of deep dielectric charging.

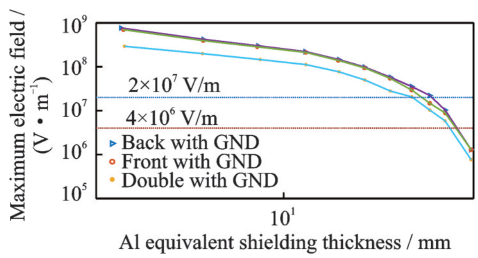

Fig.8 Maximum saturation electric field of FR4 versus shield thickness for different grounding (GND) types in Io orbit

2.3 Maximum saturation electric field versus dielectric thickness

The properties of the dielectric include density, thickness, and electrical properties. This study focuses on the effect of dielectric thickness. Six dielectric thicknesses are selected, ranging from 0.1—3.0 mm, and applied to all satellite FR4-PCB.

The maximum saturation charging electric field with changing shield thickness and dielectric thickness are shown in Figs.9—11. The maximum saturation electric field increases with dielectric thickness. With increased dielectric thickness, the num-

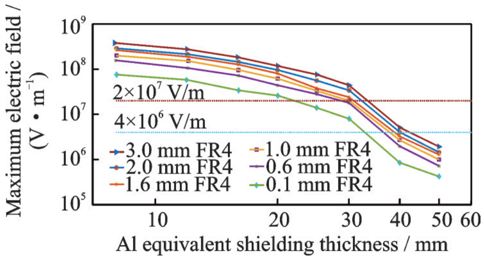

Fig.9 Maximum saturation electric field with changing shield thickness and dielectric thickness of FR4-PCB front with GND in Io orbit

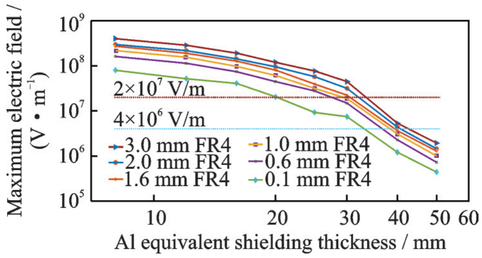

Fig.10 Maximum saturation electric field with changing shield thickness and dielectric thickness of FR4-PCB back with GND in Io orbit

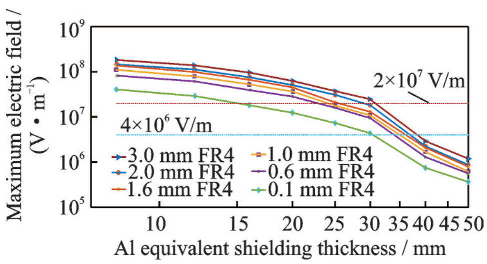

Fig.11 Maximum saturation electric field with changing shield thickness and dielectric thickness of FR4-PCB double with GND in Io orbit

ber of electrons that can deposit in the dielectric layer increases, so the electric field increases. A thicker dielectric corresponds to a greater maximum internal electric field. As shown in Figs.9—11, the ground types significantly influence the value of the charging electric field. The grounded back has the largest electric field, while the grounded front is slightly smaller and grounded double is about 50% of that of the grounded back. Grounded double can decrease the risk of dielectric charging. The safety shield thicknesses for multiple dielectric thicknesses in Io orbits following 2×10^7 V/m as the break down threshold and 4×10^6 V/m as the safety threshold for internal electric fields are shown in Tables 2—4. It is apparent that double grounded and

Table 2 Safe thickness for different glass-reinforced epoxy laminate (FR4) dielectric shield thicknesses for the front of a satellite in Io orbit, with grounded (GND) types

Dielectric thickness/ mm	Threshold	
	2×10^7 / (V•m^{-1})	4×10^6 / (V•m^{-1})
0.1	22.0	32.9
0.6	28.7	36.5
1.0	30.0	37.8
1.6	30.8	38.9
2.0	32.3	40.1
3.0	33.3	42.4

Table 3 Safe thickness for different FR4 dielectric shield thicknesses for the back of a satellite in Io orbit, with grounded (GND) types

Dielectric thickness/ mm	Threshold	
	2×10^7 / (V•m^{-1})	4×10^6 / (V•m^{-1})
0.1	20.0	33.2
0.6	27.5	36.8
1.0	29.4	38.4
1.6	30.5	39.4
2.0	32.1	40.7
3.0	33.4	42.7

Table 4 Safe thicknesses for different FR4 dielectric shields for double with grounded (GND) types in Io orbit

Dielectric thickness/ mm	Threshold	
	2×10^7 / (V•m^{-1})	4×10^6 / (V•m^{-1})
0.1	15.1	30.6
0.6	23.0	35.0
1.0	24.9	36.6
1.6	25.6	37.3
2.0	29.1	38.7
3.0	31.0	40.8

thinner dielectrics require thinner shielding. Therefore, to decrease the necessary shield thickness, double grounded and thinner dielectric should be chosen where possible.

2.4 Use of PTFE

PTFE is a common cable dielectric material widely used in space. PTFE has a lower conductivity than FR4. The maximum saturation charging electric fields under different shield thicknesses are calculated and shown in Fig.12. A dielectric thickness of 1.6 mm is used in calculations. Similar to

FR4, the maximum saturation charging electric field decreases with the increas in shield thickness. The shield thicknesses of 1.6 mm PTFE for different grounded types in Io orbits following 2×10^7 V/m as the break down threshold and 4×10^6 V/m as the safety threshold for internal electric fields are shown in Table 5.

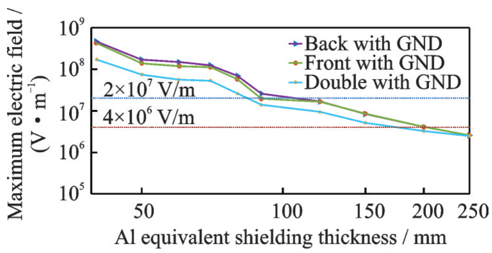

Fig.12 Maximum saturation charging electric field of 1.6 mm PTFE for different grounded types versus shield thickness in Io orbit

Table 5 Safety shield thickness of 1.6 mm PTFE for different grounded types in Io orbit mm

Grounded types	Threshold	
	2×10^7 / (V•m^{-1})	4×10^6 / (V•m^{-1})
Front with GND	89.5	200.2
Back with GND	107.0	200.2
Double with GND	84.1	176.1

The maximum saturation charging electric field with changing shield thickness and dielectric thickness for double with ground are shown in Fig.13. The safety shield thicknesses for different dielectric thicknesses in Io orbits following 2×10^7 V/m as the break down threshold and 4×10^6 V/m as the safety threshold for internal electric fields are shown in Table 6. As compared to FR4, PTFE requires thicker shielding, and dielectric conductivity can significantly affect the required shielding thickness. Lower conductivity means a higher saturation charging electric field. Therefore, to decrease the charging risk, dielectric with higher conductivity should be used, and spacecraft engineers should choose different criteria for different dielectrics.

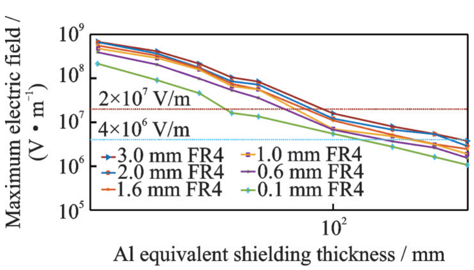

Fig.13 Maximum saturation electric field with changing shield thickness and dielectric thickness of PTFE double with GND in Io orbit

Table 6 Safety shield thickness for different PTFE dielectric thicknesses for double with grounded types in Io orbit

Dielectric thickness/mm	Threshold	
	2×10^7 / (V•m^{-1})	4×10^6 / (V•m^{-1})
0.1	47.7	120.5
0.6	71.9	143.3
1.0	77.4	169.9
1.6	83.3	175.0
2.0	86.7	221.8
3.0	93.3	241.0

3 Discussion and Conclusions

The paper is mainly about deep dielectric charging effects in Jovian planets' orbits and how to mitigate it. The purpose is to build a bridge between space physics and engineering applications and also provide some engineering design references for future Jupiter exploration plans.

The exploration of Jovian planets is a future deep space exploration hotspot. Jovian planets have a serious high-energy electron radiation environment as compared to Earth. At present, many internal charging software, such as DICTAT, are developed for Earth orbit. Most of these software are not suitable for Jovian planets because the Jupiter orbits have significant numbers of electrons at energies up to 10 MeV. In this paper, a Monte Carlo toolkit, GEANT4 and RIC method, is used to calculate deep dielectric charging effects for Jovian planets. GEANT4, developed for high energy physics, can simulate the transport and deposition processes of all possible energy particles. The simulation results are compared with criteria for preventing deep dielectric charging effects in Earth orbit. The following conclusions can be drawn.

(1) Effective criteria used in Earth orbit are not always appropriate for preventing deep dielectric charging effects in Jovian orbits. Generally, Io, Eu-

ropa, Saturn (R_S=6), Uranus (L=4.73) and Ganymede missions should have a thicker shields or higher dielectric conductivities while Neptune (L=7.4) and Callisto missions can have a thinner shields or lower dielectric conductivities. Using a standard of 0.01 pA/cm^2 as the safe incident internal flux, the safe shielding thicknesses for Io, Europa, Saturn (R_S=6), Ganymede, Uranus (L=4.73), GEO, Neptune (L=7.4), and Callisto orbit are 268.5, 53.6, 23.3, 11.0, 4.3, 2.7, 1.5, and 0.7 mm Al equivalent, respectively.

(2) Different dielectrics in different electron radiation environments require different shield thicknesses. Here, we use FR4 and PTFE dielectrics in Io orbit as a research target and 2×10^7 V/m as the break down threshold and 4×10^6 V/m as the safety threshold for internal electric fields. The required safety shield thicknesses for different FR4 and PTFE dielectric thicknesses in Io orbits are shown in Tables 2—6.

(3) In addition to the shield thickness, grounding type and dielectric thickness also significantly affect the charging electric field. Dielectrics grounded with double metal layers can significantly decrease the charging electric field and thus decrease the risk of deep dielectric charging. Thinner dielectrics produce a smaller charging electric field.

(4) Compared with FR4, PTFE dielectrics have a lower conductivity and thus a larger charging electric field. Higher conductivity can decrease the probability of discharges. Therefore, for different dielectrics, spacecraft engineers should choose different shielding thicknesses to decrease the charging risk.

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类木行星轨道卫星深层介质充电效应防护研究

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摘要：高能电子引起的卫星深层介质充电效应是造成卫星异常和故障的一个重要的空间环境效应。类木行星（包括土星、天王星、海王星以及木星的卫星）被认为具有很强的电子辐射带，可能会造成卫星深层介质充电效应。旅行者1号飞越木星期间，产生了至少42次内部静电放电事件。随着深空探测的发展，人们越来越关注类木行星轨道上的卫星深层介质充电效应。采用蒙特卡罗工具包GEANT4和辐射诱导电导率RIC模型计算了类木行星轨道上的卫星深层介质充电效应，并将结果与预防地球轨道卫星深层介质充电效应的标准进行了比较。研究结果表明，在地球轨道上行之有效的标准并不总是适用于类木行星轨道。一般来说，木卫一、木卫二、土星（$R_S=6$）、天王星（$L=4.73$）和木卫三任务应该采用更厚的屏蔽层或更高的介电常数材料，而海王星（$L=7.4$）和木卫四任务可以采用更薄的屏蔽层厚度或更低的介电常数材料。此外，介质双面接地和使用薄介质也可以降低卫星深层介质充电风险。

关键词：类木行星轨道；地球轨道；深层介质充电效应；空间辐射