A Study of Spacecraft Charging due to Exposure to Interplanetary Protons

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Abstract:

The interplanetary space environment is composed mostly of plasma from the solar wind and high energy protons from solar events such as coronal mass ejections. Satellites orbiting Earth are shielded to some degree from these events by the Earth's magnetic field but spacecraft traveling between planets are exposed to these solar protons directly. A major concern for spacecraft is internal electrostatic discharge (IESD), a form of spacecraft charging. The majority of research regarding IESD has been concerned with the electrons in the space environment around the Earth and at Jupiter; little research has been done on the charging of spacecraft in interplanetary space due to solar event protons. This paper reviews the work done so far on IESD due to protons and provides a possible example of an anomaly due to a proton induced discharge in interplanetary space on the Galileo spacecraft. Topics for further research are also suggested.

1) Introduction

Spacecraft charging remains a current topic of research and a concern for designers of both Earth orbiting and interplanetary vehicles [1]. Spacecraft, and more specifically dielectrics on a spacecraft, become charged as they interact with the charged particles of the space plasma surrounding them [2]. In Earth orbit, the majority of spacecraft charge results from the collection of energetic electrons on the surface (called surface charging) or in the bulk of dielectrics (called internal electrostatic discharge (IESD)). Many papers have been written on the both types of spacecraft charging in the environments found in Low Earth Orbit (LEO), Polar Earth Orbit (PEO), and Geosynchronous Earth Orbit (GEO) examining both the correlation between the radiation environment and failures in satellites due to discharges from the charged dielectrics [2]-[7], but few have covered the topic of charging of spacecraft dielectrics by protons as found in interplanetary space.

The paucity of papers covering this issue is not surprising since the most spacecraft flown are Earth satellites and are thus not directly exposed to the interplanetary proton environment. The radiation belts around the Earth shield orbiting craft from the full effect of solar protons. The Earth's environment is one where energetic electrons

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[1] In memory of Dr. A. Robb Frederickson who passed away April 5, 2004 while this paper was been researched and written.

dominate the effects observed on spacecraft in the outer radiation belts while protons dominate in the inner belts. Little correlation between proton flux in the inner belts and spacecraft charging has been found in Earth obit. Even on satellites designed to correlate spacecraft charging with the space environment such as the CRRES satellite did not specifically find discharges linked to proton exposure [4]. Since the majority of spacecraft charging issues in Earth orbit are due to the electron flux, the majority of papers on spacecraft charging to date have examined the effects of electrons on spacecraft dielectrics.

Spacecraft flown on missions away from the Earth, however, spend a large portion of their mission life in interplanetary space unprotected by planetary radiation belts. For these spacecraft, the issue of charging due to protons is more of a concern. The space environment between planets is dominated by the low energy plasma of the solar wind [27], a small flux of high energy particles from the Galactic Cosmic Rays (GCR), and occasional bursts of high energy protons from Solar Proton Events (SPE) such as associated with Coronal Mass Ejections (CME) or solar flares [18]. Little is known about the proton charging of spacecraft in the interplanetary environment. Work has been performed studying the effects high energy protons have on the operation of particular devices, and measurements have been taken of the composition of solar event protons in the vicinity of the Earth [17], [18], [24]-[26] and by extrapolation the composition of solar event protons in interplanetary space, but the topic of the charging due to these protons has received little attention.

With the current desire to send larger spacecraft to visit the outer planets on long-term missions, such as those planned for the Prometheus project, it seems prudent at this time to address the topic of proton induced spacecraft charging.

2) Dielectric Charging by Protons

From research performed since the late 1970's it is known that dielectrics on spacecraft can and will store charge as they are exposed to electrons in the space environment. This collected charge, whether on the surface or in the bulk of the dielectric, can build up creating large localized electric fields which can lead to discharges of mobile electrons and ions in an electrostatic discharge (ESD) pulse [4]. What is not known as clearly is if dielectrics exposed to high energy protons found in the space environment will demonstrate the same effects.

a) Review of published articles

A review of the literature for articles related to dielectric charging due to energetic protons indicated that the majority of studies on this topic have been reported by a few Russian authors over the last two decades [8]-[15]. As a generalization, their research indicates that beams of energetic protons can charge dielectrics such that discharges can occur. Closer examination of several of the key findings regarding proton irradiated dielectrics follows.

The clearest example of a discharge in a dielectric is the formation of a Lichtenberg figure. These tree-like patterns form as the material converts to plasma in the presence of high local electric fields in the path of an electrostatic discharge [20]. The discharge forms a permanent and visible trace in the dielectric material indicating the path of the discharge through the material. These figures have generally been formed in the laboratory by exposing a dielectric to high energy electrons which penetrate into the dielectric and form a layer of charge at a depth dependent on the energy of the electron beam. The stored charge forms an electric field within the dielectric which discharges rapidly when an event (often the prick of a grounded spike in laboratory experiments) localizes the electric field. At this point the critical breakdown voltage of the dielectric is exceeded and a discharge begins spreading in tree-like branches to the area near the implanted charge [16].

Lichtenberg figures have historically been formed by implanting electrons in dielectrics, but Akishin, et al. [12], [13] have demonstrated that such discharge figures can be produced in dielectrics exposed to proton beams. In one example, BK-108 and STK-120 optical glass were exposed to 100 MeV protons with a fluence of 10^{13} cm^{-2}. In glasses, the protons penetrated approximately 3 cm before stopping and forming a layer of charge. It is not stated by the Akishin, but it is supposed that a discharge was induced in the glass resulting in the formation of a Lichtenberg figure. He reports that a plasmoid was ejected from the discharge channel and electromagnetic radiation in the range of 1 to 10 MHz was generated. In the both glasses the discharge channel was approximately 100 μm in diameter and about 3 cm in length.

Discharges from proton irradiated materials were also reported by Khorasanov [15] with proton energies ranging from 10 to 70 MeV. In this experiment, Polymethylmetacrylate (PMMA) and an Epoxy Resin disks (7 cm in diameter, 5 cm thick) were exposed to proton beams with fluences from 10^{12} to 10^{13} cm^{-2}. Lichtenberg figures were reported in the PMMA samples after 10 to 50 seconds of exposure to a 30 to 70 MeV proton beam at 6×10^{-4} A/m^2. The figure creation was accompanied by both a flash of light and an electromagnetic pulse. Similar results were reported for the Epoxy Resin samples, though the fluence required prior to a breakdown in the materials was less due to the higher insulating properties of the Epoxy Resin. In both cases, when the energy of the proton beam was decreased below 30 MeV, the probability of a discharge in the dielectric materials decreased.

Other work by Gromov involved exposing sheets of Mylar (polyethylene terephthalate, PETP) and Teflon (PTFE) to 0.23 and 0.8 MeV protons to examine the surface charging and volume distribution of charge at energies typical of the solar wind [11]. The surface charge of these two materials was found to increase with time, but in a non-linear fashion attributed to "radiation and drift leakage of the implanted charge." Exposure times ranged from 3 to 9 seconds with a beam current density of 10^{-9} A/cm^2 for the 0.8 MeV protons and 6×10^{-8} A/cm^2 for the 0.23 MeV protons giving a maximum fluence of approximately 5×10^{10} cm^{-2}. An hour after exposure the distribution of volume charge was mapped for both materials using an acoustic probing method. In the 52 μm thick Mylar sheet, the 0.8 MeV protons grouped at a depth of approximately 26 μm, while the

0.23 MeV protons gathered at a depth of approximately 3 μm. In comparison, the 0.8 MeV protons penetrated the 75 μm thick Teflon sheet to a depth of approximately 18 μm.

The build up of energetic protons in the volume of a dielectric was mathematically modeled for by Boev, et al. [8], [9] for plane-parallel samples with grounded electrodes on both front and back surfaces. Boev showed mathematically that the electric fields in a dielectric exposed to protons are dependent on the change in the Radiation Induced Conductivity (RIC) of the material as it is exposed. He also showed theoretically and confirmed experimentally that the total charge in an exposed dielectric depends on both the energy of the protons incident on the dielectric and the RIC of the material due to these incident protons.

Akishin also mathematically modeled the electric fields created in a material when exposed to high energy protons. He based his equations on the mobility of electrons in the exposed materials since he argued that the protons ionize the region of the material that they pass through before coming to rest in the interior. The effect of this ionization may form an electric current within the portion of the material transversed by the protons. Using this argument Akishin developed an equation relating the energy and density of protons need to create a discharge to the material's breakdown electric field and electron mobility [14].

Based on the results of the research discussed it appears that dielectrics charged with protons can produce discharges and, presumably, discharges that could be hazardous to spacecraft. The results obtained above, however, generally came about from dielectrics charged with high fluxes of very energetic particles, a rare occurrence in interplanetary space. Thus determining the probability that a spacecraft will be exposed to sufficient energetic protons to produce a discharge is both important and difficult to convincingly prove from these experiments. Additional experimentation in more realistic situations is required.

b) Charge density calculation

One of the first things to determine for a realistic study is the quantity of protons needed to produce an electric field of sufficient strength to cause a dielectric breakdown. For most materials the field strength needed for the dielectric material to change from a solid state to plasma is on the order of 10^5 V/cm. For the sake of simplicity the parallel plate capacitor model will be used to model spacecraft dielectrics. For cases such as thermal blankets composed of thin dielectric sheets with a grounded layer of vacuum deposited metal on one side the model is appropriate. A sheet of charge due to protons in the dielectric acts as one electrode while the grounded metallic layer acts as the other. To obtain the number of protons needed involves applying Gauss' Law, given as equation (1) using MKS units.

$$\oint \varepsilon \bar{E} \bullet d\bar{s} = q \qquad (1)$$

In this formula $\bar{E}$ is the electric field created by the sheet of deposited protons, $d\bar{s}$ is the differential surface element of this sheet of charge, $\varepsilon = \varepsilon_o \, \varepsilon_r$ is the relative permittivity of the dielectric times the permittivity of free space, and q is the charge enclosed within the surface of integration. For a single sheet of charge the classic definition of the electric field emanating from both side of the surface is expressed as equation (2).

$$E = \frac{q}{2\varepsilon S} \qquad (2)$$

In this expression E is the strength of the electric field perpendicular to the sheet of charge and S is the area of the chosen Gaussian surface. For the parallel plate capacitor model where there are two sheets of opposing charges the electric field from both sheets of charge combine via vector addition. When the fields from both sheets of charge are equal in intensity the electric fields outside of the two sheets of charge cancel while the fields contained between the two sheets of charge can be expressed as (3).

$$E = \frac{q}{\varepsilon S} \qquad (3)$$

$$\rho_s = \frac{q}{S} = \varepsilon E \qquad (4)$$

In this case, the surface charge density, ρ_s, required to produce an electric field of sufficient strength to cause dielectric breakdown is given in (4) and is equal to approximately $5\varepsilon_r \times 10^{10}$ cm^{-2}. For a worst case evaluation, let ε_r=1 so that $\varepsilon = \varepsilon_o$ and the required density of protons is ρ_s=5×10^{10} cm^{-2}.

With this estimate for the required proton density before breakdowns can occur, the question becomes how likely is it that a spacecraft will accumulate this amount of charge? Several factors are involved in answering this question and not all of them are clearly understood. The first involves the flux of protons that impact a spacecraft during interplanetary flight while a second involves how long charge is maintained in an exposed dielectric.

The above parallel plate capacitor model assumes a single layer of charge a set distance from a grounded electrode. This situation can be created in a laboratory environment using monoenergetic beams, but is unrealistic in interplanetary space since the sun emits protons with a full spectrum of energies from 1 keV to hundreds of MeV. Protons with different energies will penetrate dielectric materials to different depths as illustrated in Figure 1. Low energy protons may stop at the surface of the dielectric, medium energy ones may stop in the bulk, and the highest energy protons may pass through surface dielectrics to a grounded backplane or beyond into the interior of the spacecraft. The multitude of ranges for protons of varying energies produces a charged region in spacecraft dielectrics with varying charge densities depending on fluence of protons per energy on that particular dielectric surface.

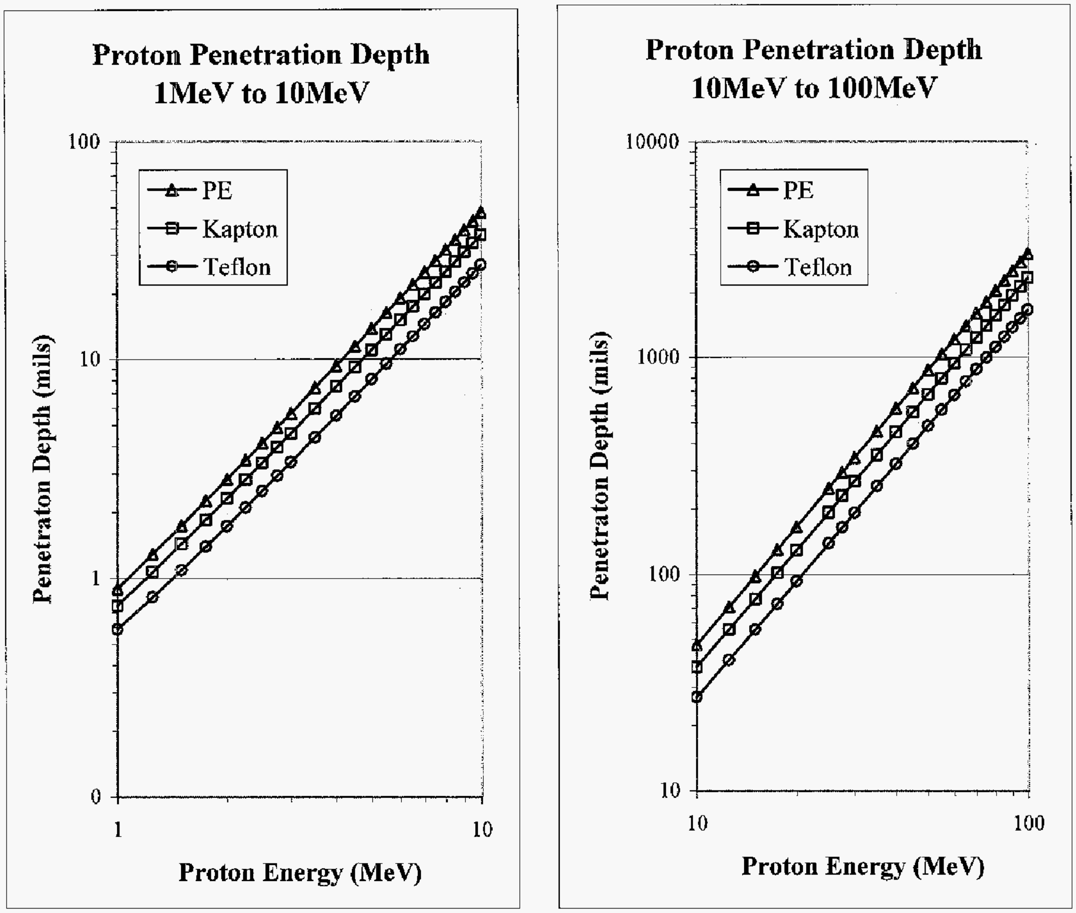
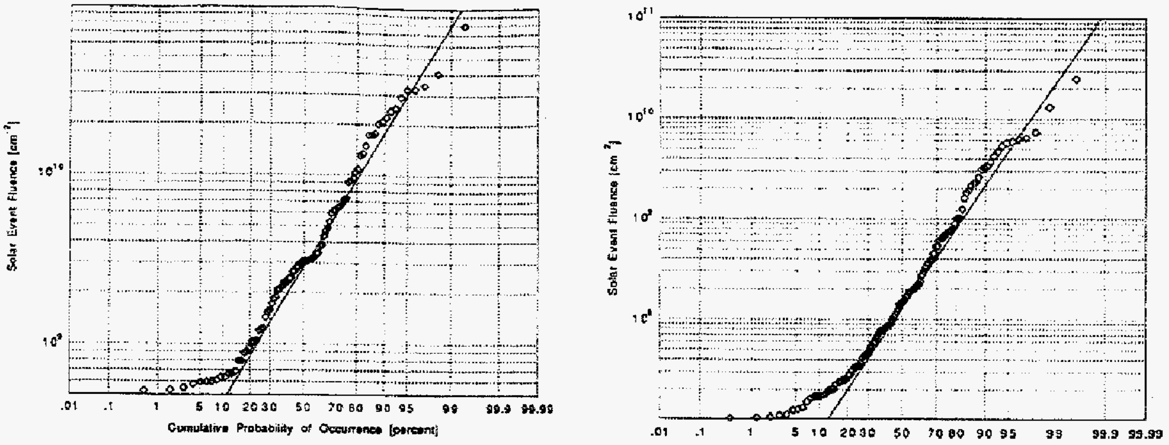


Figure 1. Proton Penetration Depths in several typical spacecraft dielectrics. Range data courtesy the National Institute of Standards and Technology [34].

The second factor in determining the possibility of dielectric breakdowns involves the conductivity of the dielectric material. Both the intrinsic dark conductivity of the dielectric and Radiation Induced Conductivity (RIC) due to exposure to high energy protons are involved with this issue. The dark conductivity for electron exposed dielectric materials has been found in recent laboratory experiments to generally be in the range of 10^{-19} to 10^{-21} Ω^{-1}cm^{-1} [28], [29] but it is not experimentally known if these conductivity values hold true for protons which may conduct at different rates due to their larger mass and decreased mobility in typical dielectric materials. Determining the conductivity of a dielectric after exposure to energetic protons is a topic for further study. The effective conductivity of spacecraft dielectrics will also be affected by radiation induced conductivity caused by ionization of the dielectric as energetic particles pass through the material [30]. The energy and intensity of the incident protons will greatly affect the RIC component of the total conductivity with greater energies presumably increasing the conductivity and reducing the ability of the dielectric to store charge.

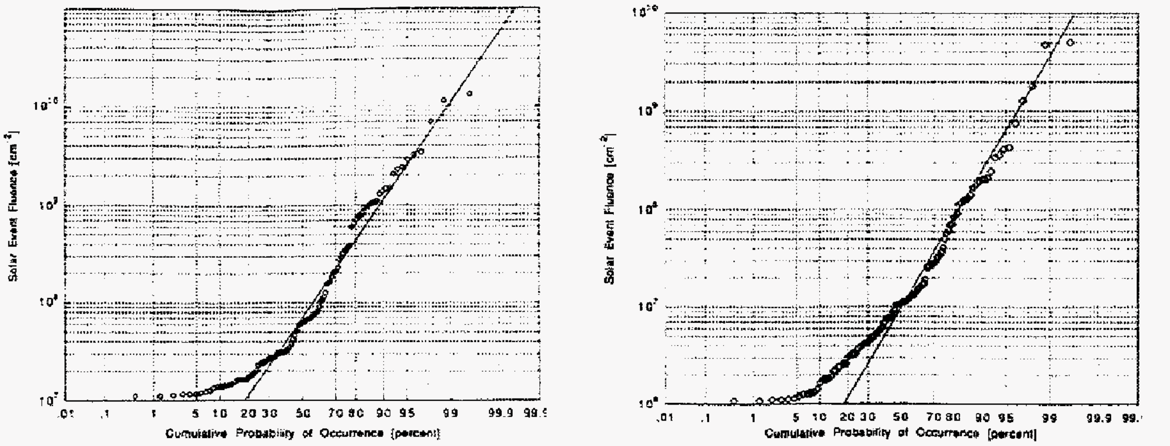
c) Solar event proton fluences

The most important sources for solar event protons are Coronal Mass Ejections (CME) which produces large numbers of high energy particles that are accelerated away from the sun. Due to the varying energies and fluxes of the solar event protons from CMEs, dielectrics on spacecraft exposed to particles from these events will contain charged particles at varying depths and charge densities inside the material. In addition, the flow of protons is not constant in either particle energy or in particle flux, but is highly time dependent.



a. >1 MeV protons

b. >4 MeV protons



c. >10 MeV protons

d. >30 MeV protons

Figure 2 a-d. Cumulative Probability Curves for four proton energy ranges from the JPL 91 model by Feynman, et al. [31].

Much work has been done by Feynman et al. and Xapsos et al. on the spectrum and fluences of particles in interplanetary space with an emphasis on the effects of large CMEs. Feynman modeled the fluence of interplanetary protons between 1963 and 1998 and created a JPL fluence model for solar event protons [31], [32]. This model includes plots for the distribution of individual solar event fluences for protons in several energy ranges. From these distribution curves, seen in figure 2 a-d, the probability of fluences of 10^{10} cm^{-2} decrease as the energy of the protons increase. As can be seen in the distribution curves, only the largest solar events will have fluences in the 10^{10} cm^{-2} range and these protons will generally have energies of less than 30 MeV.

Table 1 a-d. Fluence values for the 10 largest solar proton events for four proton energy ranges (courtesy of Feynman, et al. [31]).

TABLE *a.* Fluence Values for the 10 Largest Events in the Range Where Energy >1 MeV

Year	First Day	Last Day	>1 MeV Fluence
1989	272	314	7.92E+10
1989	225	251	4.05E+10
1978	113	130	3.43E+10
1981	126	147	3.24E+10
1989	66	80	3.23E+10
1981	281	295	2.92E+10
1991	68	102	2.50E+10
1978	44	51	2.40E+10
1982	325	357	2.20E+10
1989	331	340	2.07E+10

Read 7.92E+10 as 7.92 × 10^{10}. Values are in 10^{10} cm^{-2}. These data cover day 270 of 1972 through day 126 of 1991.

TABLE *b.* Fluence Values for the 10 Largest Events in the Range Where Energy >4 MeV

Year	First Day	Last Day	>4 MeV Fluence
1989	292	313	24.80E+9
1989	225	249	13.00E+9
1978	112	129	7.31E+9
1978	266	271	6.39E+9
1991	82	90	6.21E+9
1981	281	294	5.87E+9
1989	272	282	5.69E+9
1978	44	49	5.33E+9
1989	331	338	4.69E+9
1981	126	147	4.23E+9

Read 24.8E+9 as 24.8 × 10^9. Values are in 10^{10} cm^{-2}. These data cover day 270 of 1972 through day 126 of 1991.

TABLE *c.* Fluence Values for the 10 Largest Events in the Range Where Energy >10 MeV

Year	First Day	Last Day	>10 MeV Fluence
1989	292	313	13.10E+9
1972	201	233	11.30E+9
1989	225	249	6.89E+9
1989	272	288	3.41E+9
1991	82	98	3.23E+9
1978	266	271	2.88E+9
1978	107	129	2.42E+9
1969	89	113	2.30E+9
1981	281	294	2.06E+9
1971	25	30	1.49E+9

Read 13.1E+9 as 13.1 × 10^9. Values are in 10^{10} cm^{-2}. These data cover day 331 of 1963 through day 126 of 1991.

TABLE *d.* Fluence Values for the 10 Largest Events in the Range Where Energy >30 MeV

Year	First Day	Last Day	>30 MeV Fluence
1972	173	232	50.20E+8
1989	292	311	47.30E+8
1989	225	244	18.10E+8
1989	272	282	12.90E+8
1991	82	89	7.59E+8
1978	266	269	4.31E+8
1981	281	291	4.15E+8
1984	116	122	3.60E+8
1971	24	29	3.41E+8
1978	118	123	2.47E+8

Read 50.2E+8 as 50.2 × 10^8. Values are in 10^{10} cm^{-2}. These data cover day 331 of 1963 through day 126 of 1991.

Feynman also compiled tables for the fluences for the top ten solar proton events in the time period covered in the JPL 1991 model. These tables are reproduced here as Table 1 a-d. Note that for protons with energies greater than 1 MeV, the fluences were always greater than 10^{10} cm^{-2}, but this is only true for two events both the greater than 4 MeV and greater than 10 MeV ranges.

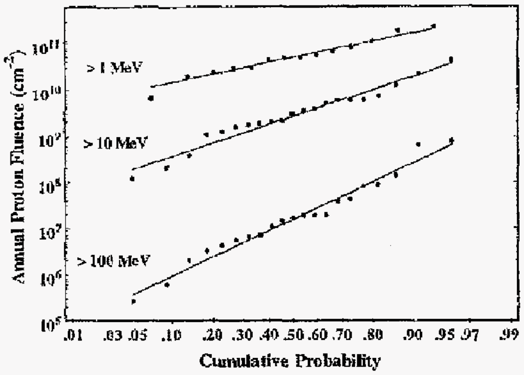


Figure 3. Probability plot for cumulative annual proton event fluence observed at 1 AU during solar active years in three energy ranges. (Courtesy of Xapsos et al. [24])

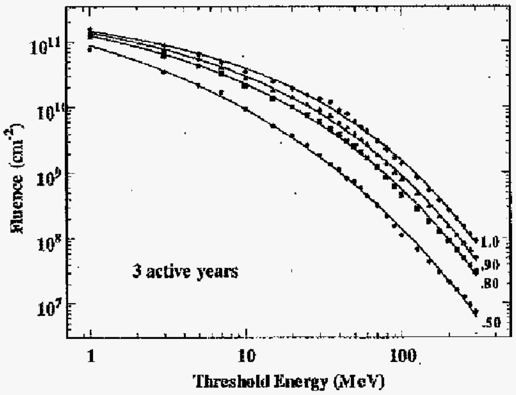


Figure 4. Worst case solar proton event energy spectra at confidence levels of 0.50, 0.80, 0.90, and 1.0 for a mission duration of 3 solar active years. (Courtesy of Xapsos et al. [17])

Xapsos created probability models for cumulative and worst case solar event proton fluences [17], [33] based on data from 1967 through 1996. The results of the cumulative probability study, seen in Figure 3, indicates that during one solar active year 1 MeV protons will almost always have fluences of higher than 10^{10} cm^{-2} while protons with energies of 10 MeV will rarely reach that level. For the worst case situation, seen in Figure 4, Xapsos predicts solar event protons of up to 30 MeV could have fluences of at least 10^{10} cm^{-2} but this would be a rare event.

From the work of Feynman and Xapsos, it appears that fluences of 10^{10} cm^{-2} are not uncommon for protons with energies near 1 MeV, but as the energy of the particles increases, the fluences drop so that only the very largest solar events will produce large enough protons fluences of 10 MeV or above to cause dielectric breakdown.

3) Anomalies on the Galileo Spacecraft

No documented cases of a spacecraft event due to proton charging have yet been recorded even though multiple craft have been flown in interplanetary space. This fact does not in and of itself preclude discharges on spacecraft due to proton induced dielectric charging as most of the spacecraft were in their minimally active "cruise" stage while traveling between the planets. Since it is thought that protons do not pose a threat, sensors that might detect a discharge have either been turned off while in cruise mode, or not included in the spacecraft payload. To find a possible example of a proton induced discharge, it is necessary to look for secondary events and for upsets to particularly sensitive equipment that was in operation in interplanetary flight. A spacecraft that might show the effects of a proton induced discharge is the Galileo orbiter.

a) Galileo design

The Galileo spacecraft was designed to gather scientific data from both stably mounted remote sensing instruments and from rotating field and particle science instruments. To accommodate both types of instruments, the spacecraft was designed with two separate parts, the spun side containing the communication equipment, fields and particle science equipment, thrusters, power generators, and the primary Command Data System (CDS) computer, and the despun side with another CDS computer and the scan platform containing the Solid State Imager (camera), spectrometers, and a photopolarimeter [21]. Since the spun side contained the main computer, communications, and the spacecraft power supply, the two sides had to be both mechanically and electrically linked for proper operation through with a Spin Bearing Assembly (SBA) which allowed the spun side of the spacecraft to rotate without moving the stationary despun side. Electrical connections between the two were accomplished by using rotational transformers for high speed data transmission and a system of slip rings and brushes for low frequency, power, and ground connections.

The spacecraft chassis was floated between the high and low terminals of the power supply to allow the mission to continue even if a short developed between one side of the power supply and the chassis at some point in the mission. The slip rings and brushes transferred all of these power lines between the two sections of the spacecraft along with power returns, structural grounds, and several control lines for the despun CDS power on resets and bus resets [21].

Soon after launch on October 18, 1989, the spacecraft began reporting that the power supply was no longer balanced at the chassis ground indicating the presence of some lower resistance path between the chassis and one side of the power supply. This bus imbalance first occurred for the DC power supply at launch plus 48 days and for the AC power supply at launch plus 63 days. Since the spacecraft was designed to operate normally with a single fault short, the imbalances seen in the AC and DC bus voltages at the chassis did not harm the mission but a simultaneous short to the other side of the power supply at the same time could have disabled the spacecraft.

A great deal of effort was put into characterizing the bus imbalances to determine what was causing them, if they could be fixed, and if the mission could still continue. Over the span of four years, it was decided that the most likely source for the low resistance paths was a collection of metallic debris in the Spin Bearing Assembly (SBA) that was creating a short between two or more slip rings or brushes. No other explanation found satisfied the data returning from the spacecraft. The low resistance paths, called debris shorts, seem to have been made by bits of the brush or slip ring materials that had been worn away during the normal operation of the assembly. These bits of conductive material clumped together and provided an electrical path between adjacent rings or brushes causing a short and an associated imbalance in the bus voltages at the chassis. The AC bus imbalance seemed to remain relatively constant over the life of the Galileo spacecraft, but the DC bus imbalance changed in value at various intervals during the spacecraft's lifetime with little correlation to any other event.

Starting in March 1991 the Command Data System (CDS) on the despun side of Galileo began to experience Power on Resets that caused the whole spacecraft to go into a safing mode. These resets were non-periodic and unpredictable occurring only nine times between launch and the arrival at Jupiter. Based on the experience with the AC and DC bus imbalances, these computer resets were blamed on the creation of debris shorts between the Power on Reset (POR) command lines in the SBA and another slip ring. While this explanation fits with the problems encountered with the bus imbalances the despun CDS resets do not follow the general pattern of the bus voltage imbalances to be able to definitely claim that debris shorts were the definite cause.

Recent work by Fieseler et al. [22] seems to indicate that there may have been an environmental cause for the despun CDS resets. In his work examining the effects of radiation on the Galileo systems while in orbit around Jupiter, Fieseler noted that the despun CDS resets that had been absent for five years restarted in 1998 after the E16 orbit (target moon Europa, 16th Jovian orbit) when the orbiter was moved into orbits inward towards Jupiter's high radiation regions. From this point on from 0 to 3 despun CDS resets were noted for each pass by Jupiter with a large majority of the resets occurring after the spacecraft made its closest approach to Jupiter.

The resumption of resets to the despun CDS after the spacecraft began to pass within 10 R_J seems to indicate that some phenomenon occurred to restart problem of Power on Resets (POR) for this computer. Fieseler argues that it was the increase in radiation dose that Galileo received while in close proximity in the planet that caused the resumption of the despun CDS resets. He notes that the star scanner aboard the spacecraft can be used as a form for radiation monitor and that there seemed to be a minimum of 1500 counts during the duration one orbit before a reset occurred. The increase in radiation dose would cause the spacecraft to become charged to a high potential such that electrostatic discharges would likely occur in the spacecraft dielectrics causing current spikes in the spacecraft electronics. These spikes are the probable cause for the resumption of despun CDS resets.

If dielectric discharges are the cause for despun CDS resets on the Galileo spacecraft while in orbit around Jupiter, it follows that they could be one of the mechanisms for the resets experienced by the spacecraft during the cruise phase of the mission. During the cruise phase, however, the primary particles that could have charged dielectrics on the spacecraft and caused dielectric discharges were solar event protons.

b) Cruise Stage Upsets

Since these despun CDS upsets occurred while Galileo was in its cruise phase, the instruments on board that could have recorded the presence of protons around the spacecraft were not in operation. This fact makes showing that the resets were caused by proton bombardment more difficult due to uncertainties in the composition of the space environment around Galileo. The best method of associating despun CDS upsets with the presence of energetic solar event protons is to try to correlate the spacecraft upsets with known solar events in both space and time. To be able to correlate either one it is necessary to look at how solar event protons propagate through the solar system.

From a basic point of view, the Sun produces the majority of the particles that make up the space environment in the solar system. Electromagnetic radiation and the low energy plasma that constitutes the solar wind are continuously emitted from the solar surface. The plasma, with a net neutral charge, moves out from the Sun in an approximately radial path at an average speed of from 400 to 1000 km/sec. The magnetic field of the Sun is "frozen" into the plasma as it moves away into the solar system so the magnetic field lines form a spiral pattern as solar wind moves outward and the Sun rotates. The pattern of magnetic field lines formed by the movement of the solar wind and the rotation of the Sun closely resembles an Archimedes spiral to a first order approximation. When higher energy protons are emitted from Coronal Mass Ejections (CME) or solar flares, the charged particles tend to follow the same spiral magnetic field line paths created by the movement of the solar wind. As a result, energetic protons tend to take a more looping path through the inner solar system.

Since the only methods for measuring the presence of solar event protons available during time of the despun CDS upsets were the GOES-6 and -7 satellites in orbit around the earth, the only correlations possible are when Galileo was in or near the magnetic field line path of particles that would emanate from the Sun, pass and be recorded at Earth, and continue on the Archimedes spiral path of the solar wind through the inner solar system.

To establish this kind of correlation, the position of the Galileo spacecraft in relation to the Earth and the Sun was plotted using polar coordinates. In this graph, the Sun is located at the origin and the Earth is left fixed as a set location 1 A.U. from the origin.

The Satellite Orbit Analysis Program (SOAP), by the Aerospace Corporation, was used to locate the Galileo spacecraft at the time of the despun CDS upsets in terms of distance from the Sun and the angle formed between the Earth, the Sun, and the Galileo spacecraft. Relative position data is given in Table 2 and plotted in Figure 5.

Table 2. Date of despun CDS upsets with Galileo's position relative to the Sun and the angle made between the Earth, and the spacecraft.

	Date of despun CDS reset (mm/dd/yy hh:mm)	Galileo/Sun Distance (A.U.)	Earth, Sun, Galileo angle (degrees)
1	3/26/91 13:30	1.22	16.597
2	5/3/91 5:26	1.46	3.769
3	7/20/91 2:09	1.88	-40.507
4	6/10/93 16:53	2.34	-61.528
5	6/17/93 18:22	2.40	-66.681
6	7/10/93 20:16	2.59	-83.971
7	7/12/93 1:37	2.60	-84.906
8	8/11/93 22:35	2.83	-109.085
9	9/24/93 0:00	3.13	-144.630

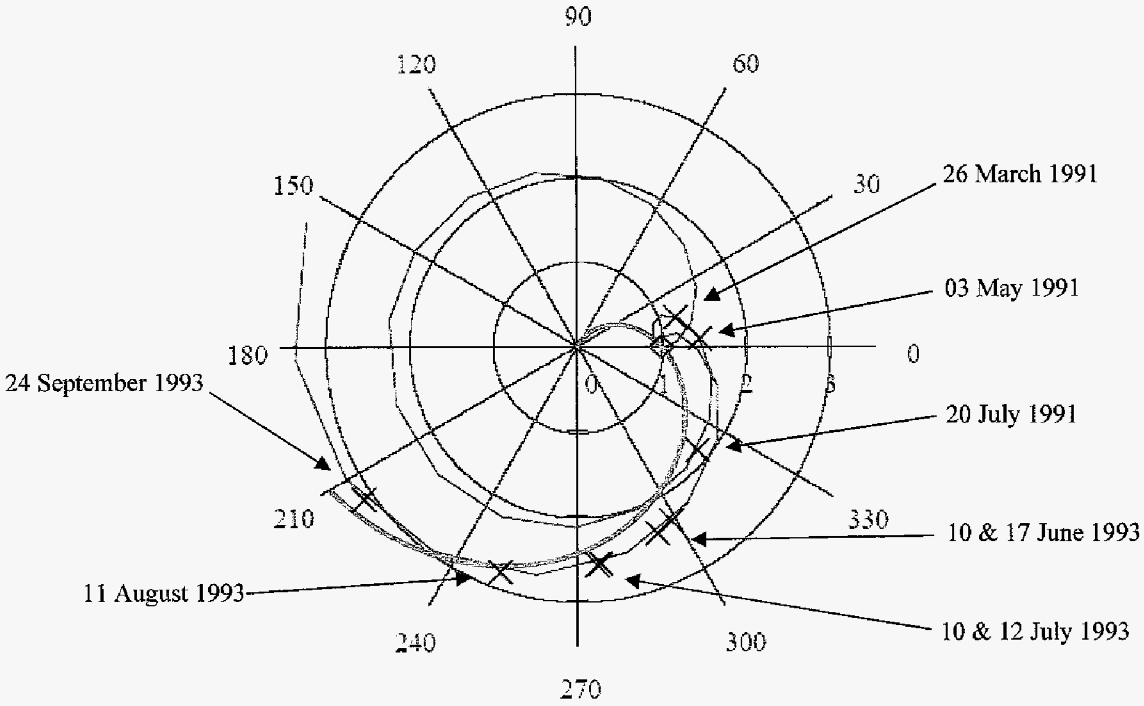


Figure 5. Relative position of Galileo vs. the Earth at the time of each cruise stage despun CDS upset. The Earth (the blue diamond ◊) is shown resting on a representative approximate solar magnetic field line (red spiral). Keeping the Earth and Sun fixed, the track of Galileo for 1991 through 1993 is shown (brown line) with the position at each despun CDS reset marked (black X's). Note that solar field lines are in constant motion and the representative field line is shown only to indicate the approximate path of solar event protons. (Generated by use of the SOAP code)

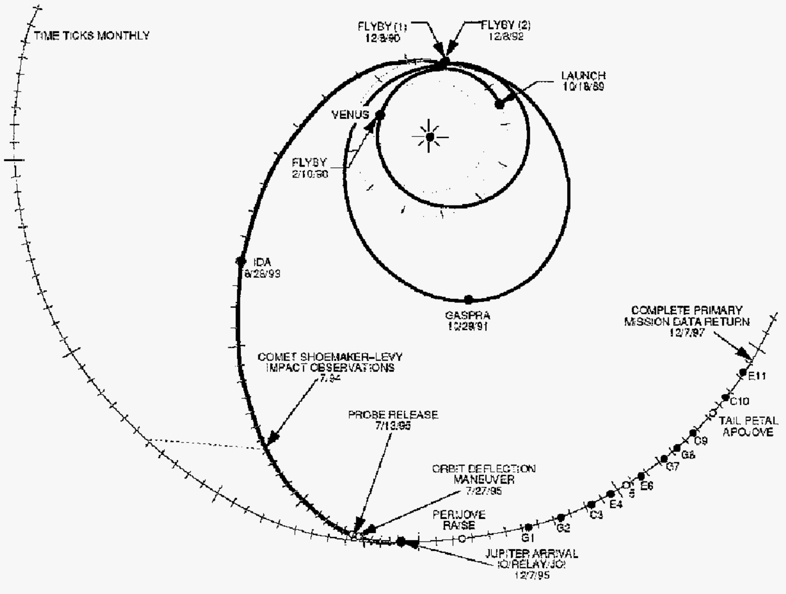


Figure 6. Unmodified flight path for the Galileo spacecraft. Labeled VEEGA (Venus, Earth, Earth, Gravity Assist) for the looping path and gravity assists needed to propel the spacecraft to Jupiter.

Using this information the location of the spacecraft was plotted in relation to the fixed reference points of the Sun and the Earth. An Archimedes spiral representing the path that solar event protons would take was plotted on the same graph such that the spiral passed by the Earth at 1 A.U. and continued through the solar system. The resulting graph is shown as Figure 5 while Figure 6 shows an unmodified view of Galileo's flight path.

One of the most intriguing features of this plot is that Galileo was in or near the path of a field that connected the Earth and the Sun at the time of all nine cruise stage despun CDS upsets. While the path of Galileo after its last gravity assist encounter with Earth put it on a path that made this possible, the spacecraft also spent the most of the two years between the first three upsets in 1991 and the last six upsets in 1993 in a path far away from the field lines as they made contact with Earth. Multiple other field lines existed for solar event particles to take all the way around the Sun, but upsets seemed to have only occurred when the spacecraft was near a field line that could connect it to Earth. For the purposes of this study this outcome is fortunate since it allows the solar environmental data gathered at Earth to have some bearing on the environment around Galileo at the time of the despun CDS upsets.

Plots of the proton environment around Earth were obtained from NOAA GOES-6, and GOES-7 satellite data [23] time periods bracketing each despun CDS upset. These plots show the flux of protons in several energy levels as recorded in Earth geosynchronous orbit and give an indication of solar event protons present around the spacecraft during these time periods. For the three despun CDS resets that occurred in 1991, there is some correlation between the time of a reset and an increase in solar protons as recorded by the GOES satellites.

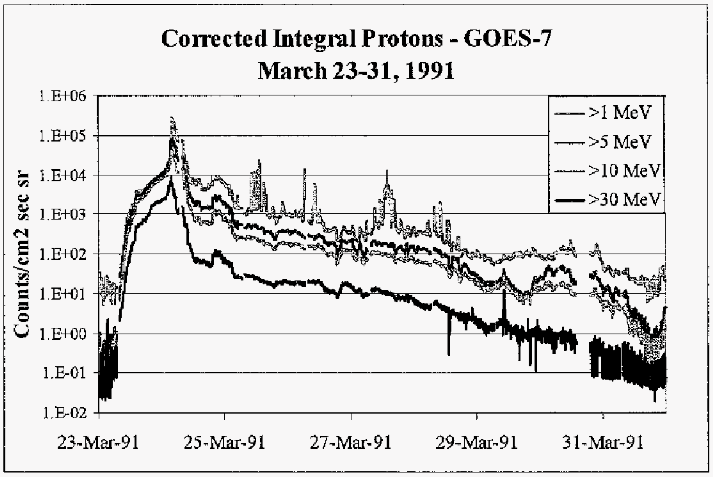


Figure 7. Proton fluences at the end of March 1991 at 1 A.U. from the NOAA GOES-7 satellite. Fluences are plotted in four energy ranges: >1 Mev; >5 MeV, >10 MeV; and >30 MeV. A large Coronal Mass Ejection can be seen beginning on March 23 with heightened proton fluences recorded through the beginning of April.

For the first reset, May 26, 1991, there was a strong increase in the proton flux starting on May 23 indicating a solar event as seen in Figure 7. The increased proton levels lasted into the first part of April. During that time, Galileo was at approximately 1.2 A.U. in close proximity to Earth having just completed that first of its gravity-assist Earth flybys. It is reasonable to say that the solar event protons that the GOES satellites recorded also interacted with the Galileo spacecraft. Since the first despun CDS reset occurring in this environment, it is quite possible that the solar event protons could have been a contributing factor to the computer upset.

The second upset, May 3, 1991, did not have a significant solar proton event just prior to the upset, but it is possible that protons from the May solar event could have charged up dielectrics on the spacecraft and not discharged until a month later. It is not known how long dielectrics exposed to energetic protons will remain charged, but the possibility exists. The third despun CDS upset in 1991 occurred on July 20, 1991 after an extended period of moderate solar proton activity as recorded by the GOES satellites. The spacecraft was at approximately 1.9 A.U. at the time, but still close to the approximate magnetic field line path connecting the Earth and the Sun. This upset did not occurring during the peaks of solar proton activities as recorded by the GOES satellites, but it is possible that protons accumulated on spacecraft surfaces during the month of exposure and built up an electric field of sufficient strength to cause a dielectric discharge that could have coupled into the POR circuit for the despun CDS.

After the despun CDS upset in July of 1991, there were no more recorded upsets until June of 1993. The reason for this gap in time is not known. The spacecraft moved away from the path of solar protons from the Sun to the Earth, but solar activity was still recorded on Earth so it is reasonable to assume that the Galileo spacecraft was still being exposed to fluxes of solar event protons of varying degrees of energy and intensity. Any discharges that occurred during this time must have either been small enough to have little impact or have affected instruments that were not active. When resets did resume in June of 1993, the frequency and intensity of solar events had decreased. Some correlation between the despun CDS upsets and increases in solar proton counts on the GOES satellites can be made for the upsets that occurred on June 10, June 17, and August 11, 1993, but the increases in solar protons were small compared to the events in 1991.

4) Could a Discharge due to Protons cause a Despun reset?

It seems from the data that there is not a unique correlation between solar event protons and the despun CDS upsets, but it is possible that discharges from dielectrics on the spacecraft could have caused some of the computer upsets if not necessarily all of them. The exact cause for the upsets is not known leaving room for additional explanations. It is also possible that the same spacecraft fault, the despun CDS going into a POR condition, could be caused by events on the spacecraft. It is reasonable then to explore a dielectric discharge as a potential explanation for a despun CDS reset.

For simplicity, the Galileo spacecraft can be modeled as a simple dipole with the center of the dipole on the Spin Bearing Assembly (SBA) as in figure 8. The actual electrical nature of the spacecraft might have been more complex in specific areas, but for this analysis a simple dipole is sufficient. With this model, solar event protons have charged up one side of the spacecraft to a high positive potential. The electric fields caused by the collection of positive charge on one side of the spacecraft cause the movement of negative charge to balance the electric field within the conductive chassis. The spacecraft as a whole will have a positive potential as compared to the neutral space plasma surrounding it, but the chassis of the spacecraft will have formed a dipole with the more negative side toward any proton charged dielectrics.

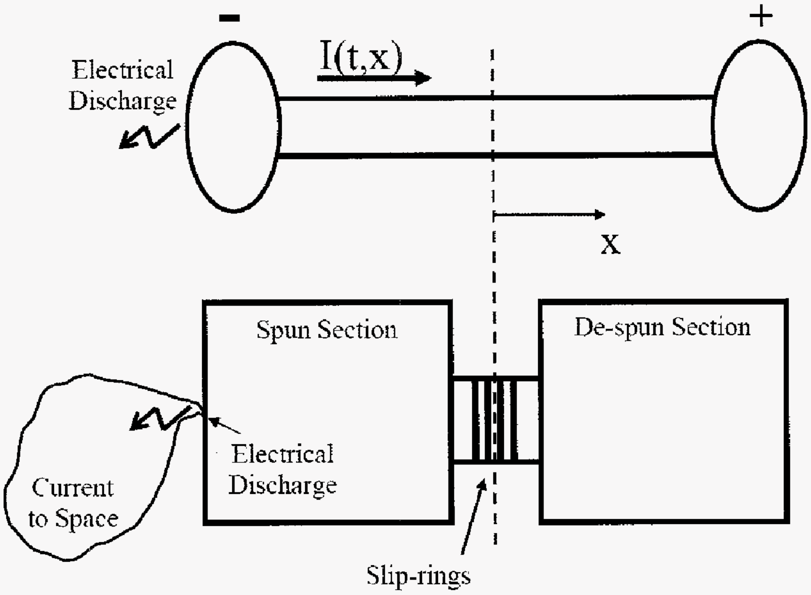


Figure 8. Simplified model of the Galileo spacecraft as a dipole and in its separate sections.

When a discharge occurs, the positive charge stored in a dielectric is expelled reducing the electric field at the point of discharge. Negative charges that had been balancing the positively charged protons immediately move to maintain charge neutrality in the conductive chassis creating a current spike. For a bus balanced spacecraft such as Galileo, a current spike in the chassis is a current spike in the spacecraft electric ground. Magnetic fields caused by the movement of charge would also induce other current spikes in inductively coupled wires on the spacecraft. The maximum amplitude of the current spikes would occur at the center of the chassis dipole at, or near, the Galileo SBA where the current spike in the ground or induced spikes in other signal lines could trip the power on reset flag creating an upset in the despun computer.

Other mechanisms exists for a despun CDS upset from a dielectric discharge including direct exposure of the computer circuits or signal lines to the discharge plasma created during the formation of a Lichtenberg figure discharge, but induced current spikes are the most likely result from a discharge and one that would not require close proximity to the despun CDS unit itself.

List of Proton Charging Issues for Further Study

- Under what conditions will protons induce dielectric discharges? Are there sufficient fluxes of protons in interplanetary space to produce breakdowns?
- How long are protons stored in space-based dielectrics? Are conductivities determined for electron exposed dielectrics that same for proton exposure?
- What are the shapes of typical discharge spikes for proton induced discharges? How do they compare to those from electron induced discharges?
- What are the specific risks to spacecraft spending long periods of time in interstellar space?
- What are the design rules for preventing or mitigating the effects of energetic proton charging of spacecraft?

As in the case of electron IESD, we need to develop specific design guidelines for protecting spacecraft from proton IESD and develop methods for evaluating their efficacy. While this may be a much longer term goal, it is probably the most important for this project.

5) Conclusion

Spacecraft charging due to exposure to energetic solar event protons is a topic that is not well understood and has received little attention in the space community. Most spacecraft charging in Earth orbit is due to energetic electrons so the majority of studies have concentrated on electron charging of spacecraft surfaces and spacecraft dielectrics. While this concentration is adequate for Earth orbital missions, spacecraft that travel in interplanetary space for extended periods of time will more likely to be exposed to energetic protons emitted by the Sun during solar events such as Coronal Mass Ejections. These energetic protons can charge dielectric surfaces on the spacecraft to high potentials to the point were dielectric discharges may occur.

Dielectrics highly charged by exposure to energetic protons have been shown to discharge in laboratory experiments indicating that sufficient breakdown electric fields can be generated by the accumulation of positively charge particles.

An example of a spacecraft fault that could have been caused by proton induced dielectric discharges is given in the despun Command Data System (CDS) upsets on the Galileo spacecraft. There is some correlation between the time of the despun CDS upsets on Galileo and periods of intense solar activity though the spacecraft survived the October 1989 solar event without evidencing dielectric discharging. Proton charging, and the current spikes along the spacecraft ground and induced in other spacecraft systems caused by rapid dielectric discharging, could have been a contributing factor for the upsets recorded in the Galileo despun CDS.

Additional research is needed to characterize dielectric charging by protons including gaining more understanding into the amount of fluence of protons required to produce a dielectric discharge, the shape and characteristics of proton induced discharge spikes, and determining the degree to which charge is stored in dielectrics after energetic proton exposure. Additionally, mitigation techniques are needed to reduce the risk of spacecraft failures due to proton charged dielectrics. These issues are of particular importance for spacecraft that intend to spend extended periods of time in interplanetary space. Examples of these spacecraft are the Jupiter Icy Moons Orbiter (JIMO) mission, Project Prometheus spacecraft, and Mars missions during times of high solar activity.

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