Charge Production due to Leonid Meteor Shower Impact on Spacecraft Surfaces

William J. McNeil
Radex, Inc., Bedford, MA 01730

Shu T. Lai   Edmond Murad
Air Force Research Laboratory
Hanscom AFB, MA 01731

Abstract. The Leonid meteor shower is expected to hit the Earth's atmosphere with high flux in mid November, 1998 and 1999. The flux will probably be the largest in thirty years. It may hit again with potentially nearly the same order of magnitude in November, 2000. The meteoric dust flux is expected to be more intense and encompass shorter time, the dust velocities will be faster than any other meteor storm, and the mass distribution will favor larger particle masses than normal. In anticipation of this upcoming meteor events, we endeavor to estimate the degree of possible adverse effects of the Leonid on spacecraft systems. We calculate the impact probability, the impact penetration depth, the amount of ionization generated upon impact, discuss possible impacts of the ionization on spacecraft systems and the scientific measurements onboard, suggest two potentially hazardous scenarios of sudden discharges caused by meteor impacts, and compare the charge production rate with the ones during an average annual Leonid shower.

1. Introduction

Meteor showers enter the Earth's atmosphere at fairly predictable periods every year. They are mostly of cometary origin. The cometary dust and particles travel along the same orbit approximately with dispersion, most of them lagging behind the comet. One can try to predict when and to what degree the Earth intersects the cometary orbit. When the dust and particles in orbit are too near some large planets, which may nearly intersect that of the comet, the dust and particles' orbital velocities are perturbed. Besides, new outbursts may erupt from the comet when it is heated by the Sun. As a result, both the timing and magnitude of meteor showers can be predicted fairly as probabilities only; they defy exact predictions. The Leonid meteor shower returns for a few days in November every year. Its visual zenith hourly rate (ZHR), which peaks around November 17-18 in recent decades, varies yearly and reaches a maximum every 33.25 years approximately. The Leonid normal peak ZHR is about 10 to 20 visual meteors per hour. The 1966 Leonids featured peak ZHR at 160,000 per hour [*Brown and Arlt*, 1997]. The next big Leonid shower, or storm, may occur in 1999.

Meteor showers affect the ionosphere [*Grebowsky et al.*, 1998]. As meteors ablate in the atmosphere, meteoric metal atoms, typically Na, Mg, Fe, K, and Ca, etc., are released in vapors and interact with atmospheric species [*McNeil, et al.*, 1995; 1996; 1998]. The excited or ionized metal atoms and ambient molcules enable meteor trails or fireballs to be visible. Meteors at supersonic speeds can give rise to sonic booms. Besides the occasional meteor showers, there is meteoric or cosmic dust falling almost constantly into the atmosphere everyday. The almost constant background dustfall is due to the gravitational attraction and orbital sweeping of the Earth traveling through the practically stationary meteoric, or cosmic, dust particles in the interplanetary space. The dustfall has slower atmospheric entry velocity than meteor showers but with about the same composition as the showers [*Hughes*, 1975]. Both the background dustfall and the meteor showers are responsible for the formation of metal atom layers in the ionosphere. The metal atoms and ions generate characteristic airglows [*Gérard and Monfils*, 1974; *Gardner, et al.*, 1995; 1999]. In recent years, it has been observed repeatedly that sudden layers can form at typically 83 to 110 km altitudes in a few seconds and last for hours or minutes. Sporadic E-layers, which have defied explanations for decades, are now often observed to be associated with the sudden metal layers.

Direct meteoric hits on spacecraft are space hazards. A direct hit may cause adverse effects such as plasma generation, surface and instrument damages, spacecraft anomalies, or even spacecraft loss. In recent years, the sudden failures of geosynchronous communication satellites [*Baker, et al.*, 1998], such as ANIK-1, AT&T Telstar, and Motorola Galaxy-4, caused loss of communication services to millions of customers. Microelectronics are becoming smaller, run on less current, and are more susceptible to smaller disturbing currents. In view of the upcoming Leonid meteor storms in 1999 and, perhaps, later years, and the projected rapid increase in the number of spacecraft deployed in the next century, the space community, including NASA, has already begun to realize the importance of spacecraft interactions with meteor storms.

2. The Leonid Meteors

The Leonids are the strongest of all periodic meteor showers. They are associated with Comet Tempel-Tuttle. The Leonid meteor particles enter the Earth's atmosphere at 71 $km.s^{-1}$ which is the fastest of all meteor showers. Therefore the Leonids have the highest kinetic energies. Furthermore, the mass distribution (Figure 1) of Leonid meteor particles appears to strongly favor particles larger than those of the average meteor showers. With the larger than normal meteoric particle mass and the fastest velocity, the effect of impacts on spacecraft should not be overlooked.

For example, a Leonid meteoric particle of 0.1 gm, say, impacting on a spacecraft solar cell may have similar effects as a bullet hitting it. The meteor particle impact may also impart sufficient momentum to cause significant change in the dynamics of spacecraft. Even a calcium atom, for example, released from a Leonid meteor particle ablating in the atmosphere, would have such a high velocity that its kinetic energy may reach about 1 keV (Figure 2). Such an energy is more than sufficient for hyperthermal reactions, which occur in the trapped radiation belts but do not normally occur in the ionosphere. For example, a titanium dioxide surface is normally stable in space, but reacts at hyperthermal energies. The fast atomic impact can also penetrate into materials generating an ionization track, which may cause anomalous currents or signals in cables or even initiate an avalanche discharge in differentially charged systems.

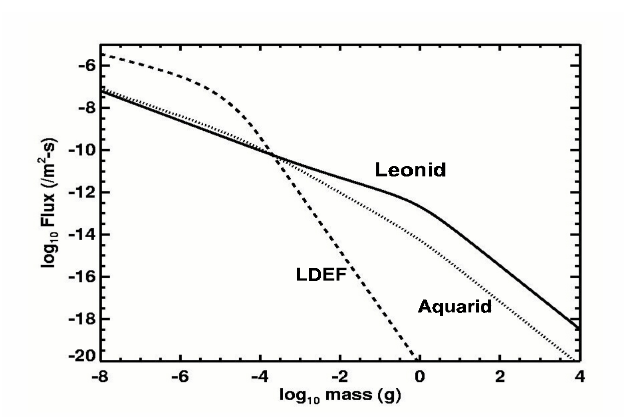

Figure 1. The cumulative flux of particles larger than a given mass for the Leonids (solid) with an assumed ZHR of 1000, for the η-Aquarids (dotted), a srong annual shower, and for the cosmic dust background according to LDEF measurements [*Love and Brownlee*, 1993] which impacts the Earth constantly. Note that the Leonids are more populous in larger particles.

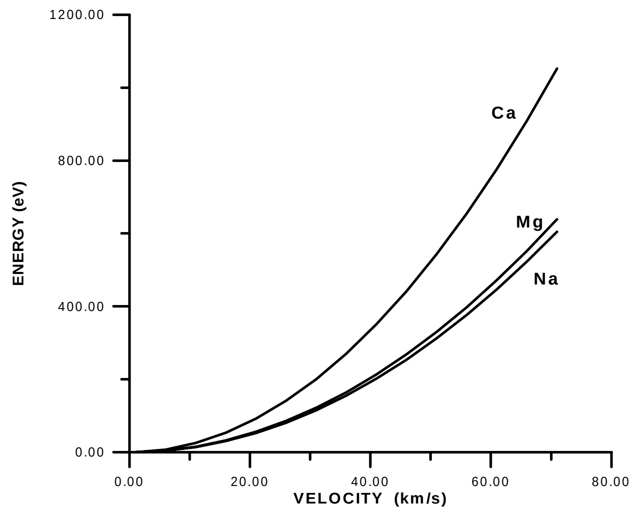

Figure 2. Energy as a function of velocity for various meteoric atoms.

3. Meteoric Impact Effects

3.1 Depth of Penetration We can calculate the depth of penetration by a particular Leonid meteor in any material from the empirical formula obtained from laboratory experiments by *McDonnell et al.* [1997]:

$$\frac{f}{d_m} = 0.7658\ d_m^{0.056}\left(\frac{\rho_m}{\rho_T}\right)^{0.476}\left(\frac{\sigma_{Al}}{\sigma_T}\right)^{0.134} V^{0.806}$$

where ρ_m is the meteor density, ρ_T the density of the target, σ_{Al} the tensile strength of aluminium, σ_T the tensile strength of the target, V the velocity in km/s and d_m the meteor diameter in cm. The calculation shows that a 1.3×10^{-5} gm Leonid particle at 71 km/s would penetrate 0.35 mm into a typical solar panel mylar surface, and a 2.9×10^{-4} gm Leonid particle would penetrate 1 cm into aluminium.

3.2 Impact Probability

The impact probability P_N for N hits is given by:

$$P_N = \frac{(FA\Delta t)^N e^{-FA\Delta t}}{N!}$$

where A is surface area normal to the flux F, and Δt is the duration of the storm. The meteoric flux is expected to remain unattenuated from the top of the atmosphere down to about 110 km where meteoric ablation [*McNeil, et al.*, 1995] with the atmosphere begins. Practically all spacecraft orbits are well above 110 km. Therefore to calculate the impact probability, there is no need to consider the attenuation of meteor flux as a function of altitude. For a major Leonid storm (such as that of 1966) of flux $F \approx 8.63\text{x}10^{-8}$ m^2/s lasting for 2.5 hours, a spacecraft of a typical size $A \approx 20$ m^2 (such as that of DSCS) would risk a 1.3% probability of a meteor hit. For a normal Leonid shower of $F \approx 4.69$ m^2/s, the probability is 0.008%.

3.3 Sudden Perturbation of Angular Momentum

To estimate the effect on angular momentum, let us take, for simplicity, a spherical spacecraft of mass $M = 10^5$ gm, radius R = 2 m, with an light instrument panel extending to 10 m. A Leonid meteor of velocity v = 72 km/s, mass m = 0.1 gm, colliding with the tip of the extended instrument panel would add an angular velocity $\Delta\omega$ given by

$$I \, \Delta\omega = m \, v \, r$$

where I is the moment of inertia of the spacecraft, m = 0.1 gm, v = 72 km/s, and r = 1200 cm. For a sphere, the moment of inertia is given by $I = (2/5)\, M R^2$. The result is $\Delta\omega \approx 0.035$ Hz.

3.4 Plasma Generation

Meteor impact on a surface is energetic enough to generate a plasma cloud coming off the surface. *McDonnell et. al.* [1997] obtained from extensive laboratory experiments an empirical formula for the electron charge production Q from aluminium surface due to a particle impact:

$$Q = 0.1\, m \left(\frac{m}{10^{-11}}\right)^{0.02} \left(\frac{V}{5}\right)^{3.48}$$

where m is the particle mass and V its velocity. We have calculated the charge production rate for minor, moderate and major Leonid showers of ZHR = 100, 5000, and 150000 respectively. Assuming a population index of 1.8 for the Leonids [*Brown and Alt*, 1997] we obtain the total charge production rates: $2.0\text{x}10^{-10}$, $1.8\text{x}10^{-8}$, and $3.1\text{x}10^{-7}$ C m^{-2} s^{-1}.

3.5 Neutral Gas Generation

It is well known that meteors ablating with high velocities in the atmosphere can suddenly fragment, vaporize, and burn up as a fireball. Meteor impact on spacecraft surface can vaporize and form a large cloud of neutral gas. An upper bound of the amount of neutral gas released can be calculated by assuming that all the kinetic energy is converted into heat energy and then divided by the vaporization energy per molecule. The result is usually many orders of magnitude larger than the plasma generated. Since neutral gas does not cause any direct damage, this aspect is usually overlooked by researchers. We shall discuss later that this aspect has serious implications.

4. Implications of the Effects

The results obtained above enable quantitative, though still crude, measures for gauging possible consequences of meteor impact. We discuss the implications of the impact probability, angular momentum, impact penetration, plasma generation, neutral gas release, and combinations of the above.

The impact probability for the scenario considered implies that the probability of impact is 1.3 % for the spacecraft considered for a major Leonid storm of 2.5 hours. In reality, the storm would likely last longer albeit tapering off. There are hundreds spacecraft in orbits. Many more spacecraft are expected to be launched into orbits next century, rendering a total probability exceeding unity. The extent of damage done in such a collision, in sofaras satellite survivability is concerned, is uncertain.

The added angular velocity to the model spacecraft considered is 0.035 Hz only. Such a small perturbation may not have significant effect by itself. However, it offers a means to detect or diagnose a meteoric hit, since a spin jerk can be accurately recognized in the telemetry data collected on the ground. Although a hit by an orbiting debris, which is much slower but may be larger, may give a jerk of similar magnitude, the direction of the hit would be different from that of a meteoroid. Therefore the two type of hits can be differentiated in the data diagnosis.

The depth of Leonid meteoric impact penetration of mm and cm orders of magnitude into surface materials is alarming. It implies that the Leonid particles, which are the fastest of all meteor showers, can cause physical damage on spacecraft surfaces, surface instruments, mirrors, windshield glass, solar panels, and even astronauts if walking outside.

We have found that the amount of plasma generation, as calculated by using McDonnell's formula, for a Leonid particle impact is insignificant. The electron flux generated is found to be $2.0\text{x}10^{-10}$, $1.8\text{x}10^{-8}$, and $3.1\text{x}10^{-7}$ A/m^2 corresponding to ZHR of 100, 5000 and 150000 respectively. As a comparison, the average quiet time ambient flux on SCATHA at near geosynchronous altitudes is 0.115 nA/cm^2 [*Purvis, et al.*, 1984]. Thus, the meteor impact generated charge flux is less than the ambient flux at quiet times on SCATHA. Thus, we conclude that the plasma produced by meteor impacts is not going to cause any significant spacecraft charging.

The ambient flux from the space plasma is in steady state but the meteor impact plasma generation from a nearby surface is sudden. The suddenness can make a difference. For example, during Langmuir probe operation, the current-voltage slope, which is most useful for sensing the ambient plasma condition, can be disturbed by a sudden change of current generated from a nearby surface. The magnitude of slope change can be calculated for a given Langmuir probe and impact plasma production. The effects of a sudden current on many systems can also be expected. Thus, we recommend shutting down all non-essential surface instruments during a meteor shower.

The implication of the neutral gas release is significant. This is because the amount of neutral gas exceeds the plasma generated by orders of magnitude. If the neutral gas remains neutral, nothing much would happen. If the plasma generated plays the role of seed ions and electrons initiating an avalanche of ionization of the neutral gas, a sudden hazardous discharge may ensue.

5. Sudden Hazardous Discharges

While the exact causes of spacecraft losses are different in each case and are usually engineering specific (depending on the geometry and usage of the instruments, for example), we merely wish to illustrate here the idea of sudden discharge hazards due to meteor impact. A simple scenario will suffice for this purpose. Suppose a meteor impacts a solar cell. Electrons, ions, and neutral gas are

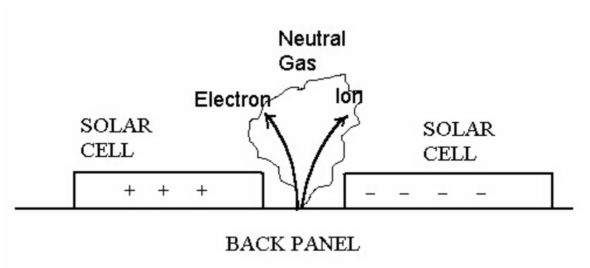

Figure 3. Electrons, ions, and neutral gas produced as a result of a sudden meteor impact near the solar cells.

generated. An electric field between the cells may accelerate the electrons and ions, ionizing some of the neutral gas molecules. The newly created electron and ion pairs are also energized by the electric field and may ionize further, provided Townsend's criterion [*Lai*, 1989a] is satisfied. If the neutral gas becomes ionized, the total charge produced would be much larger than that produced without the neutral gas.

The situation is similar to a critical ionization velocity (CIV) discharge [*Lai, et al.*, 1989b] with an important difference, namely, the energy source in our case is the external electric field whereas the source in CIV is the velocity. The efficiency of energy transfer in CIV is delicate, relying on the excitation of lower hybrid waves. In our case, however, the energy transfer is straightforward, using an external electric field to accelerate electrons and ions. Since the amount of neutral gas exceeds the initial plasma by orders of magnitude usually, we can conclude that the neutral gas is the most important factor in mediating discharges and even avalance discharges. This important conclusion applies not only to the scenario of meteoroid impact induced discharges, but also to broad types of spacecraft and laboratory discharges. We recommend laboratory experiments to firmly prove and demonstrate it.

Another hazardous scenario concerns deep dielectric charging. Before we describe this scenario, an introduction is in order. In the radiation belts, and less severely in the geosynchronous environments, the ambient electrons and ions often reach MeVs and beyond. These energetic electrons and ions can penetrate deeply into materials and stay there for days and weeks depending on the conductivity. These events are often significant in a few days after a coronal mass ejection (CME), which the Sun sends out occasionally. A CME cloud is an energetic plasma cloud. When a CME cloud reaches the Earth's outer magnetosphere, it compresses, and changes the direction of, the magnetic field lines, accelerating electrons to very high energies. If the electrons deposited inside dielectric

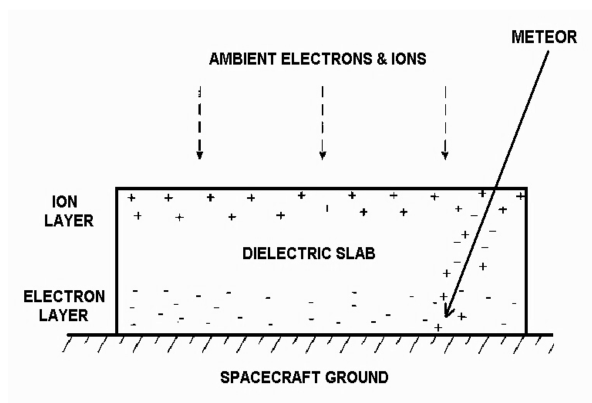

Figure 4. An ionization channel produced by a meteor impact. The channel may initiate a hazardous discharge in a differentially charged system.

materials reaches an electric field of 10^6 to 10^8 V/m [*Hastings and Garrett*, 1996], dielectric breakdown would occur. Due to the low conductivity, it is conceivable that very high electric fields can develop in dielectrics.

In space and in the laboratory, electron flux is orders of magnitude larger than ion flux because of the mass difference. Therefore, electrons deposited inside dielectrics are much more abundant than ions. In the MeV energy range, electrons penetrate (to 10^2 mil) much deeper than ions (10^{-1} mil) [*Hastings and Garrett*, 1996].

During a CME passage, dielectrics are impregnated with electrons. After the passage, the ambient plasma becomes much less energetic but denser. Now the ambient low energy ions are attracted towards the dielectric surface. A double layer is formed inside the dielectric [*Lai*, 1998]. This has potential for a hazardous discharge. All one needs is a spark, so to speak, to ignite the discharge. A meteor hit can provide such a 'spark' for ignition.

6. Conclusions

The Leonid meteor showers, the fastest of all meteor showers, have a particle mass distribution favoring larger ones than the average showers. The Leonids meteor flux increases by two orders of magnitude during major storms, which recur every 33.25 years approximately. In view of the large and increasing number of spacecraft in orbits, the total probability of meteor impact on spacecraft is significant. Meteor impacts on spacecraft not only can penetrate into the surfaces, suddenly perturb the spacecraft momentum, but also produce suddenly both plasma and neutral gas along, and coming out of, the penetration track. Such impacts may initiate hazardous discharges between solar cells or differentially charged surfaces.

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