Model of Plasma Dynamics and Electromagnetic Pulses Associated with Hypervelocity Particle Impacts on Satellites

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Abstract

We present the first results from a model that describes the interaction of a hypervelocity particle with a spacecraft, which can result in electrical damage. Though a meteoroid impact on a spacecraft can cause mechanical damage, a hypervelocity impact will result in the vaporization and ionization of the meteoroid and part of the spacecraft, forming a plasma that rapidly expands into the surrounding vacuum. We propose a mechanism for the generation of an electromagnetic pulse by this plasma. This electromagnetic pulse could be the source of electrical anomalies on a number of satellites. We also present a model of the impact process and plasma expansion. We use this model to predict the total charge generated, plasma temperature profile, density profile, expansion speed, and the spectrum of radiation from the limited information known about the meteoroid impact. The total charge generated, which is calculated from first principles, is overestimated since the plasma expands in a state of partial ionization, but the dependence on projectile mass and velocity agrees well with experiment. Plasma temperatures of up to 25 eV and expansion speeds of up to 40 km/s are predicted. The model is most accurate for high velocity impacts (>30 km/s).

1 Introduction

Spacecraft must be protected against many natural hazards of the space environment. The design, performance, and reliability of spacecraft and ground-based support systems are heavily influenced by these hazards. A component of the space environment that is only partially understood is the impact of meteoroids on spacecraft. Man-made debris is also in orbit around Earth; while this debris can potentially damage satellites, it is traveling much slower than most meteoroids (7 km/s, as opposed to meteoroids which travel at speeds of 11 to 72.8 km/s).

An impact event could cause anywhere from minor to catastrophic damage to spacecraft systems. Larger meteoroids tend to cause mechanical damage, though their sparsity means that this type of damage is extremely rare. Impacts of smaller and faster meteoroids, which are much more numerous, can result in electrical anomalies since the total generated charge is a very strong function of meteoroid velocity. A number of satellites have been affected by electrical anomalies associated with hypervelocity impacts, including Olympus during the Perseid meteoroid shower in 1993 and Landsat 5 during the same shower in 2009. The link between impacts and spacecraft electrical anomalies is not well understood. Electrical effects include electrostatic discharges (ESDs) and electromagnetic pulses (EMPs). Hypervelocity impacts will vaporize and ionize the projectile as well as a fraction of the target material, creating a plasma. The dynamics of this plasma are responsible for EMPs. Plasmas generated from hypervelocity impacts were first observed by Friichtenicht and Slattery [1].

2 Model

There are a few reasons to develop a physical model of hypervelocity impacts. Besides the obvious desire to understand the physics behind this process, there are ground experiments being performed to measure the plasma and radio frequency (RF) radiation from impacts. It is currently impossible to reproduce the exact conditions of a hypervelocity impact on a satellite. Light gas guns, Van de Graaff accelerators, and meteoroids represent very disparate masses and velocities. In addition, the condition of the satellite, such as charging, spin rate, orbit, and orientation with respect to the background magnetic field also contributes to the resulting electrical effects from an impact. The model is used to design sensors for these ground experiments and to account for any differences caused by experimental apparatuses.

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The objective of a hypervelocity impact model is to predict all relevant plasma parameters from the limited information known about the impact. The initial parameters are meteoroid mass, velocity, material, impact angle, target material, and background atmosphere. For the purposes of this model, the impact angle is neglected and the background atmosphere is assumed to be of low enough density to be considered a perfect vacuum. The desired parameters are the plasma density profile, temperature profile, expansion speed, and the power spectral density of the RF radiation from the plasma. A precursor to this model is given in [2].

The first objective is to estimate the total charge generated from a meteoroid impact. It is estimated that the minimum speed necessary to vaporize the projectile is around 10 km/s [3], which is well below typical meteoroid speeds. For meteoroid velocities (50+ km/s), the projectile is entirely vaporized and nearly all of the plasma is made up of ions from the target material. The plasmas generated from slow projectile impacts (<10 km/s) and fast projectile impacts (>30 km/s) will have distinct characteristics.

The impact creates a strong shock wave in the target material which expands spherically outwards from the point of impact. The energy behind the shock is high, but it decreases as the shock expands. At a certain time after impact, there is no longer enough energy to vaporize the target material. The shock in the target material is modeled as a spherical blast wave expanding into a homogenous background. This is a classic problem in fluid mechanics with a self-similar solution; it is solved in [3-4]. The radius of the blast wave is given by $R_s = \alpha t^{2/5}(E/\rho_t)^{1/5}$, where E is a portion of the kinetic energy of the meteoroid, ρ_t is the density of the target material, t is time, α is a similarity parameter which is approximately $\alpha \approx \Gamma - 0.4$, and Γ is the ratio of heat capacities of the target material. The energy per unit mass contained within the blast wave is

$$L = \frac{3E^{2/5}}{4\pi\rho_t^{2/5}\alpha^3 t^{6/5}}. \tag{1}$$

An implicit assumption in Equation 1 is that none of the energy escapes into the vacuum while the blast wave vaporizes the target material. On this short time scale, nearly all of the vaporized fluid is moving towards the blast wave and not out into the surrounding vacuum, and thus the energy remains in the cavity until the point where vaporization ceases. In order to vaporize the target material, L must be a factor β greater than the specific heat of vaporization. Using this fact with values of R_s and L leads to the total vaporized target mass.

The temperature is calculated by partitioning the total kinetic energy from the meteoroid. A portion goes into vaporizing the incident projectile. Energy is also lost to the target vaporization and ionization processes. The remaining energy is the thermal energy of the plasma. The ionization state of the gas in the cavity is found by the Saha equation. This calculation must be iterated since the electron temperature is decreasing as ionization occurs. This method supposes the plasma ionization process runs to completion in the short time that the plasma is collisional, but the relaxation time for the plasma to thermally ionize is expected to be longer, so this method will overestimate the charge. The plasma rapidly expands into the vacuum after vaporization, so it will quickly become collisionless and thus freeze into a state of partial ionization. The generated charge must be reduced by a factor that is a function of the vaporization time and the ionization relaxation time.

The sudden expansion of fluid into a vacuum is another classic problem in fluid mechanics. It is solved with the method of characteristics in [5]. For uniform initial density and pressure, the boundary of the ion fluid expands with speed $u_b = 2c_s/(\gamma - 1)$, where c_s is the initial speed of sound. There is an exchange of thermal energy for kinetic energy, and the plasma is considered cold ($T = 0$) while expanding into the vacuum. For a plasma expanding into a quarter of a sphere, the electron density is

$$n_e(t) = n_{e,0}[1 + t(\pi\rho_t u_b^3/3M_v)^{1/3}]^3, \tag{2}$$

where $n_{e,0}$ is the initial electron density inside the cavity after vaporization and M_v is the total vaporized mass. Due to the impulsive nature of a hypervelocity impact, a significant population of surface electrons will separate together from the ions and oscillate in phase at the plasma frequency. The plasma ballistically expands into the vacuum, with electrons moving out first due to their higher mobility. The macroscopic charge separation causes an electric field, which pulls the electrons back. As the ions expand into the vacuum, the electrons oscillate around the ion front. This coherent oscillation is the radiation mechanism.

We define the separation of the electron population with the background ions to be $\xi(t) = r(t) - u_b t$. In a single dimension, Poisson's equation yields $E = -n_e e\xi/\epsilon_0$, where E is the electric field, e is the electron charge, and ϵ_0 is the permittivity of free space. The pressure gradient, gravity, convection, and radiation reaction were shown to be second order. The equation of motion for this plasma is $\ddot{\xi} = -\omega_p^2 \xi$, where the plasma frequency, ω_p, is a function of time. This equation has an analytic solution, but the WKB solution is sufficient. It is given by

$$\xi(t) = -\frac{u_b}{\omega_{p,0}}[1 + t(\frac{\pi\rho_t u_b^3}{3M_v})^{1/3}]^{3/4} sin[\frac{\omega_{p,0}}{2}(\frac{3M_v}{\pi\rho_t u_b^3})^{1/3}(1 + t(\frac{\pi\rho_t u_b^3}{3M_v})^{1/3})^{-1/2}], \tag{3}$$

where $\omega_{p,0}$ is the initial plasma frequency defined by $n_{e,0}$. Once the motion of the electron shell is known, the power spectral density of the radiation is found by means of the Lienard-Wiechert potentials.

It is possible to generalize this to a three dimensional spherical geometry where the equations are solved numerically using Lie-group methods. The Earth's magnetic field is also included in the three dimensional numerical solution. The magnetic field can induce an anisotropic bulk plasma expansion. It can also affect the radiating electron shell by effectively setting a lower limit to the frequency of radiation at the electron cyclotron frequency. The predictions in Section 3 are obtained from the three dimensional case. The choice of initial density distribution in the plasma can have significant effects on the expansion. Since the plasma rapidly expands into a collisionless state, the density distribution freezes into the plasma. Initial distributions can result in slightly different limiting expansion speeds. An appropiate initial temperature and density gradient could also cause nonlinear steepening, and thus a shock at the boundary between the plasma and vacuum.

3 Predictions

The model can be used to predict a variety of parameters. Figure 1 shows an empirical measurement of the total charge on the left, and a calculation of total charge using the model in Section 2 on the right. The empirical equation used to generate Figure 1 is from Drolshagen [6], but there are many variations with velocity exponents ranging from from 2 to 4.7. In Figure 1, a velocity exponent of 3.48 is used. For velocities greater than 30 km/s, the calculation and empirical measurement disagree by a nearly constant factor. The overestimation is due to the fact that the plasma becomes collisionless before ionization completes. The factor is thus a function of the ionization relaxation time and the vaporization time. We also attribute this constant offset to an efficiency factor that describes the conversion of projectile kinetic energy into the vaporization and ionization processes. Besides this factor, the mass and velocity dependence of the estimate agree very well with experiment. We believe this is the first time an analytic calculation of the total charge has been made from first principles.

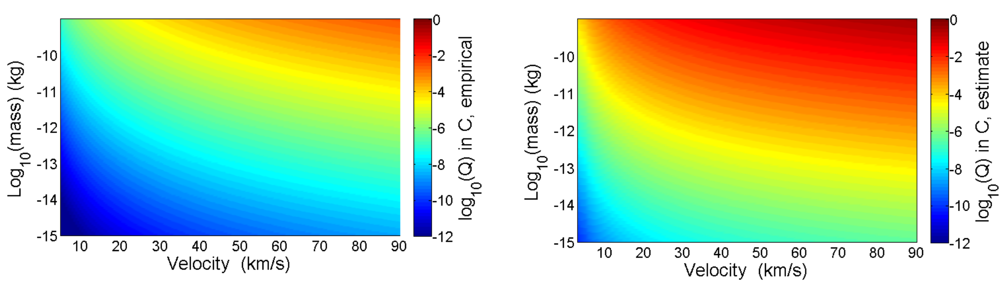

Figure 1: Charge generated from hypervelocity impact, empirical on left and calculation on right

For lower velocity projectiles ($< 30\ km/s$), the difference is greater. There are a number of difficulties in modeling these low speed impacts. The impact time for low speed projectiles is relatively long compared to other processes. The plasma is made up of ions from the projectile and from the target in similar proportions. The impact of the projectile cannot be considered instantaneous for low projectile speeds. For further predictions of plasma properties, the empirical equation for total generated charge is used. The temperature and expansion velocity are shown in Figure 2. These parameters are nearly independent of projectile mass and saturate for large projectile velocities. The power spectral density for the radiation from the coherently oscillating electrons is also shown in Figure 2. There is a strong peak near 1 GHz and a decrease until approximately 10 MHz, which corresponds to the electron cyclotron frequency.

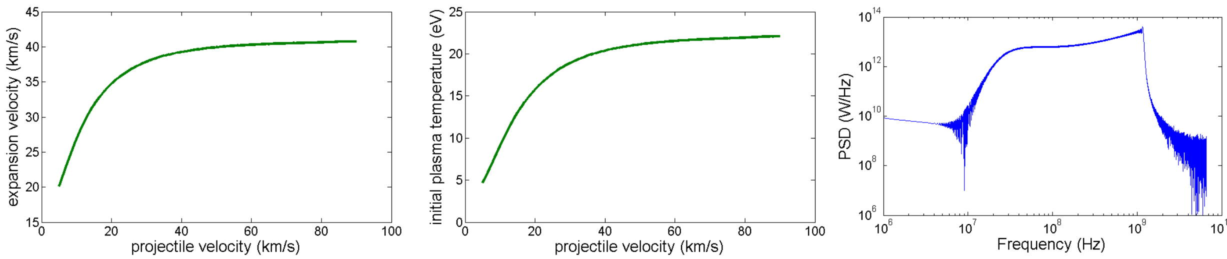

Figure 2: Plasma expansion velocity (left), initial plasma temperature (center), and power spectral density (right)

A comprehensive model of a hypervelocity impact has been presented. Given impact parameters, the resulting plasma properties were predicted. The model performs best for high velocity projectiles since there are a number of complications introduced when the velocity is low. A possible mechanism for the generation of electromagnetic pulses is derived. Our future work includes computer simulations of the impact process and the plasma dynamics, which is expected to shed light on the charge generation mechanisms and radiation mechanisms.

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