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Hypervelocity Impact Flash and Plasma on Electrically Biased Spacecraft Surfaces

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Abstract

Hypervelocity microparticles (<1µg), traveling at speeds between 11 and 72 km/s with respect to the Earth can impact spacecraft and form a small and dense plasma. This plasma can generate a strong optical emission (impact flash) and electromagnetic pulse (EMP), which can lead to spacecraft electrical anomalies when the impact spacecraft surface carries high electrical potential due to space weather events. To understand the microparticle hypervelocity impact plasma, and therefore their threat to spacecraft electronics, we need to determine the impact plasma temperature under different spacecraft charging conditions. A non-intrusive method to study the impact plasma is by measuring the optical emission spectrum. In this paper, we present a theory of how hypervelocity impact light flash is generated by the plasma, supported by experiments at a ground-based 3 MV electrostatic dust accelerator using three spectral photomultiplier tubes at 450, 550, and 600 nm. This paper is the first to presents results on hypervelocity impacts with various target electrical biases as a control variable to study the relationship between the impact plasma and the impact flash. We find that the target bias provides a strong external electric field during the initial plasma expansion and induce an ambipolar internal electric field via charge separation. Charge particle oscillation will result from the oscillating internal electric field. The impact flash is suggested to be produced by the oscillating internal electric field through acceleration/deceleration of the charge particles in biased spacecraft. We estimated the plasma temperature using the blackbody model. The result demonstrated a strong dependence of plasma temperature on the bias, which serves as the first direct experimental evidence to support that impact flash is produced by the impact plasma.

1. Introduction

The physical understanding of hypervelocity impact phenomena determines the safety of our invaluable assets in space. The mechanical damage from larger hypervelocity objects (> 1mg) when impacting onto a spacecraft are well-understood. Microparticles (<1µg) at speeds between 11 and 72 km/s cannot cause substantial or catastrophic mechanical damage upon impact, but are speculated to cause electrical damage through their impact ionization, which scales strongly with incoming speed. The microparticle-generated plasma, combined with background space weather conditions from solar activity, can produce hazardous spacecraft electrical anomalies [2,12]. Previously, ground-based hypervelocity impact experiments have been conducted using electrostatic dust accelerators [2,3,5-8,11,15], where smaller (0.1 fg to 10 pg) but higher speed particles (2 to 60 km/s) are produced [14]. Light gas gun facilities, which can accelerate particles with sizes between 1 mg and 1 g and velocities between 0.5 and 7 km/s [4,5] have also been used to study hypervelocity impact phenomena. These facilities provide a simulated experimental environment to study the hypervelocity impact. To better comprehend the electrical anomalies from the microparticle hypervelocity impact, we performed the first impact flash measurements in an electrostatic dust accelerator to characterize the impact plasma temperature under various spacecraft charging conditions and provide the first physical explanation of the optical flash connection with the impact plasma.

Upon impact, the high-speed impactor converts its kinetic energy into ionization energy and generates a dense (~10^{23} m^{-3}) but small plasma (~1µm) accompanied by strong optical flashes. One of the empirical relations commonly used to estimate the impact charge production Q is given by $Q \sim m^{1.02} V^{3.48}$ where m is the impactor mass and V is the impactor velocity [12]. Within nanoseconds after the impact, the plasma expands in the vacuum environment. As the plasma rarefies, the Debye length exceeds the size of the plasma plume and the plasma is now subject to the external electric field, which can be produced by spacecraft charging. Depending on the spacecraft surface charging conditions, the plasma can expand freely under small local instabilities and oscillations if the external electric field is mild, or create intense charge separation and plasma oscillation if the external electric field is strong. Optical [3-5,8,9], plasma, and radio frequency (RF) emission [2,4,8,11,15] are studied to understand the hypervelocity impact mechanisms for these high-speed but low-mass particles. At the heart of this hypervelocity impact problem is the understanding of the plasma dynamics and the physics connecting to its products such as RF emission, light flashes, and even catastrophic electrical anomalies. A better understanding of the hypervelocity impact physics will help improve next generation spacecraft design safety guidelines to protect against these frequent but silent "killers" in space.

The acceleration and deceleration of free electrons (through Bremsstrahlung radiation) and recombination within a plasma can generate electromagnetic radiation that can be observed through plasma optical diagnostics methods. Optical diagnostics provides an *in situ* non-intrusive measurement on the plasma with minimal plasma perturbation [10] when compared to popular plasma diagnostics tool such as a retarding potential analyzer (RPA) [2,11,15] and transient plasma analyzer (TPA) [8]. Additionally, the emission measurement can be easily measured via a simple instrument, such as a photomultiplier tube (PMT). However, optical diagnostics in plasma are generally difficult to implement because of the need for careful alignment of optical components, and the interpretation of measurement generally demands the use of appropriate physical models to connect the measurements and plasma physics [13]. Nonetheless, measuring the emission spectrum of the impact flash can provide a vital diagnostic for understanding the impact plasma using a simple blackbody radiation model. Particularly the fundamental plasma properties that can be derived from optical measurements, such as temperature and density, are needed to study the energy transport mechanism within the impact plasma and understand the hypervelocity impact physics. More importantly, the plasma temperature (mobility) is believed to be related to the impact EMP probabilities [2,11]. Thus, the characterization of impact plasma temperature is of significance to estimate the likelihood of electrical damages.

Simulations [6,8] and experimental results [5,6] strongly support the impact flash originating from the impact. For low velocity impacts < 15 km/s, Eichhorn [5] and Collette [3] have showed strong blackbody radiation behavior in the impact flash and positive correlation between the impact velocity and the blackbody temperature. However, others [2,6,8] suggest that the impact plasma exhibits significant behavior differences at velocities where it is partially ionized (< 8-10 km/s) and above where it is fully ionized (> 18 km/s). Therefore, the results from Eichhorn [5] and Collette *et al* [3] cannot represent the impact in the typical velocity regime of the microparticles. Goel [8,9] and Eichhorn [5] have also found that the impact flash intensity is a strong function of impact velocity and charge production in all velocity ranges. However, current literature lacks a physical model connecting the optical flash and the impact plasma physics. To bridge the gap, we conducted the first impact flash measurements with various target bias conditions to simulate different spacecraft charging conditions and as a control variable to aid the direct study of the plasma and optical emission correlation with extended velocity range up to 40 km/s.

2. Theory

One of the simplest ways to model a continuum optical emission from a plasma is to use Planck's law, which describes the spectral density of the electromagnetic radiation emitted by an ideal blackbody in thermal equilibrium at a given temperature. The spectral radiance I_ν of an emitting body at an absolute temperature T is a function of the emission frequency ν only, and can be expressed as

$$I_\nu(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(\frac{h\nu}{kT})-1} \qquad (1),$$

where h is Planck's constant, c is the speed of light in the medium, and k is Boltzmann's constant. Fundamentally, blackbody radiation is the photon released due to the acceleration and deceleration of electrons and is a special case of the more general Bremsstrahlung radiation, which occurs when the plasma is optically opaque. A Maxwellian velocity distribution, where the width of the distribution is the temperature T of the plasma, can be found in a thermal equilibrium plasma. In a thermal equilibrium, the plasma temperature is well-defined; whereas, the width of the velocity distribution characterizes the plasma mobility when the temperature is ill-defined. Thus, during the time the plasma exhibits thermal equilibrium or local thermal equilibrium, the plasma temperature can be estimated using the Planck's law with plasma optical spectral data, and this temperature depicts the plasma particles mobility.

The hypothesized hypervelocity impact flash model is shown in Figure 1. The impactor with mass m impacts the target at velocity v and forms a dense plasma with an empirical charge production estimation of $Q \sim m^{1.02}V^{3.48}$ [4]. When the target is biased to a negative high voltage V_{ext}, an external electric field E_{ext} resulting from this bias will accelerate the electrons outward and cause a charge separation (ambipolar) internal electric field, E_{int}, pointing in the opposite direction. As E_{int} grows in magnitude due to an increasing number of separated charge particles, the charged particles will begin to oscillate due to the competition between E_{ext} and E_{int}.

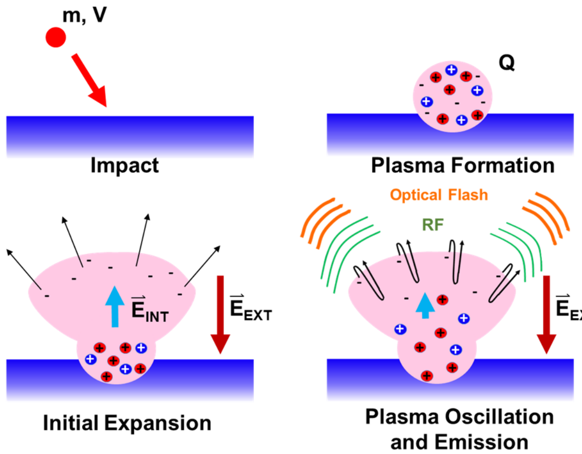

Figure 1. Hypervelocity Impact Flash and Plasma Model. A particle impacts the spacecraft, producing a plasma with total charge Q that then expands into the vacuum. As the resulting plasma expands outward, the external electric field E_{ext} due to the surface charging of the spacecraft will accelerate the electrons out first and cause a charge separation. An internal electric field E_{int} is thus created. Plasma oscillation will result from the competition between E_{int} and E_{ext}, and generate RF/optical emissions.

The impact flash can be generated by the rapid charge oscillation in the biased target**.** During the charge oscillation, the rapidly varying electric field E_{int} accelerates/decelerates the electrons causing optical emission via Bremsstrahlung (blackbody) continuum radiation. Through this mechanism, the charge particles velocity distribution is dictated by the charge oscillation frequency, and thus the strength of the E_{int}. The stronger E_{int} and oscillation tends to widen the velocity distribution and therefore raises the plasma temperature. The oscillation can also lead to RF emission from the plasma, which can increase ionization and excite the charge particles to create more photon emissions. The impact plasma continues expanding as it oscillates and emits optical/RF radiations, and becomes rarefied as the density decreases.

3. Ground-based Impact Experiment

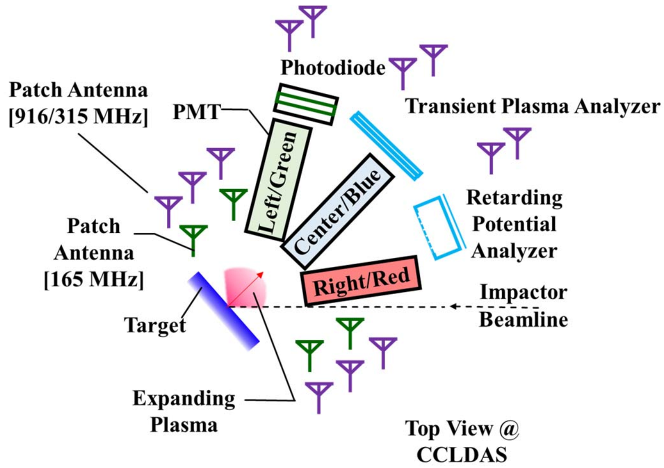

Figure 2. Top view of the test chamber with sensors and target. The impactors enter the chamber from the accelerator from right to left along the beamline shown. The target plate is angled at 28.5 degrees from the vertical. All sensors shown are mounted on a common frame. The photomultiplier tubes (PMTs) are stacked directly underneath the photodiode, transient plasma analyzer (TPA), and the retarding potential analyzer (RPA). The PMTs are at 17–18 cm from the target, and angled to focus at the expected impact location on the target.

To study the hypervelocity impact plasma and the impact optical emission, we conducted a series of experiments in 2015 using a Pelletron dust accelerator at the Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS). These ground-based hypervelocity impact events were produced by the acceleration of positively charged dust particles through electrostatic repulsion from a 3 MV terminal [17]. The experiments are conducted under a chamber pressure of less than 10^{-5} Torr within a 1.5 m chamber, which provides a mean free path (~4.3m) greater than the chamber diameter and allows the free expansion of the impact plasma representing the conditions in orbit, and with a range of iron impactor mass (0.1 to 30 fg) and velocity (15 to 40 km/s). A total of 160 impact events were studied for this paper under 11 target charging conditions ranging from -1000 to +1000 V.

We selected tungsten as the impact target material, which can produce substantial charge upon hypervelocity impact [1,7], with iron projectiles. To simulate a hypervelocity impact onto a spacecraft, the surface charging effect due to the ambient space weather condition is simulated by target biasing using a high-voltage supply. A range of biasing conditions include floating, grounded, and up to ± 1000V with respect to the chamber ground. The floating bias represents a target that is electrically isolated from the chamber, and thus allows random charge accumulation based on the ambient condition. Figure 2 shows a schematic of the experimental setup in the chamber.

4. Experimental Result and Interpretation

Stronger target biasing is found to create an enhanced ambipolar electric field during plasma expansion, which leads to an increase of plasma temperature. In Figure 3, we see a strong correlation between the target bias magnitude and the temperature. This observation directly supports our theory that stronger target biasing leads to a stronger ambipolar electric field by enhancing the charge separation during plasma expansion. Consequently, a wider velocity distribution and higher temperature in the plasma is expected as E_{int} increases. The lower mean temperature in floating target events can arise from the lack of a stable initial E_{ext} to create strong and lasting charge separation. Thus, the E_{int} is weaker in the floating events since the target plate charges can freely readjust themselves to maintain quasi-neutrality as the plasma expands. Similarly, the grounded event also lacked a strong ambipolar electric field and resulted in a lower mean temperature. Thus, the result presented in Figure 3 supports that the optical flash is directly from the impact plasma since the target biasing level has direct effects on the impact plasma produced.

In Figure 3, the positively biased events have a slightly higher mean temperature than the negatively biased events. This might be a result from the slower oscillation frequency in positively biased runs during plasma expansion, and thus a wider velocity distribution is established for the same charge production and bias potential in magnitude. Despite having a higher mean velocity in the negatively biased events, the velocity distribution is narrower and thus lower in temperature when compared to positively biased events.

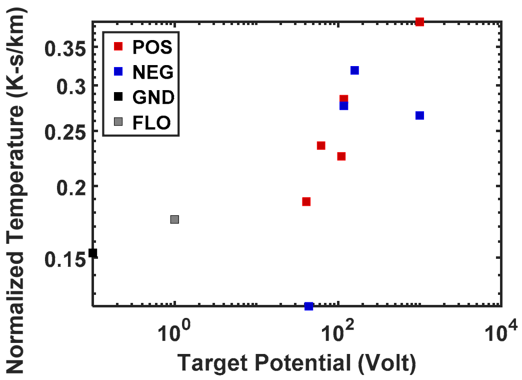

Figure 3. The mean signal peak temperature normalized by impact velocity is shown against various target bias levels on tungsten. The mean signal peak temperature was taken by averaging the signal peak temperature among the same target bias impact events. The grounded and the floating bias impact events had lower mean temperature around 3500K, whereas the biased impact events showed a positive correlation between the target bias voltage and the normalized mean temperature. This positive correlation was qualitatively extrapolated towards the grounded potential level, and the temperature converges roughly with the mean temperature measured in the grounded events. Additionally, the positively biased impacts exhibited a higher mean temperature than the negatively biased impacts.

5. Conclusion

The impact flash was found to be generated from the impact plasma, rather than target surface heating, and emitted blackbody radiation in the early time after impact. The impact flash was primarily produced by the oscillating ambipolar electric field E_{int} through acceleration of the charge particles for a biased target. Since the target bias level controlled the E_{int} strength, an increasing bias can enhance the plasma temperature. Thus, we expect higher likelihood of RF emission and electrical anomalies from these impact plasmas. In real-world scenario, the spacecraft surface can be charged to these biases easily via space weather events and experiences similar impact conditions like those shown in this paper.

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