ABSTRACT

The space environment can pose many unique hazards to spacecraft. One of these possible hazards stems from the meteoroid and debris populations that spacecraft can encounter. Traditionally mechanical damage has been the primary concern, but it has been shown that impactors with masses too small to cause significant mechanical damage have the potential to generate damaging electrical effects. These electrical effects can be further exacerbated by different spacecraft charging conditions. Meteoroids and orbital debris, collectively referred to as hypervelocity impactors, travel between 7 and 72 km/s in free space, and upon impact with a spacecraft convert their kinetic energy to ionization/vaporization energy over a very brief timescale. The result of this impact is the creation of a small, dense, and expanding plasma with a strong optical flash and possible radio-frequency (RF) emission. The impact generated plasma can also induce strong RF emissions and arc discharges depending upon the charging potential of the spacecraft. To better understand the relationship between the impact parameters and the resulting emission of optical and RF radiation, ground-based tests were conducted under a variety of impact conditions. The ground-based experiments were performed using the light gas gun facility at NASA Ames Vertical Gun Range (AVGR) for low velocity impacts (< 8 km/s), and using the Van de Graaff dust accelerator at Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS) for high velocity impacts (> 15 km/s).

This paper presents the successful deployment of a sensor suite to detect simultaneous RF, optical, and plasma measurements across a range of impact conditions at the CCLDAS and AVGR facilities. The electrical effects due to the impact were found to be related to the spacecraft charging condition, and is connected to the time evolution of the impact generated plasma.

Key words: Meteoroids; Hypervelocity; Impacts.

1. INTRODUCTION

Naturally occurring meteoroid populations can pose a significant hazard to the spacecraft that they come into contact with. This hazard traditionally stems from the possible for catastrophic mechanical failure in the event of a collision with a meteoroid of sufficient mass. However, impacts with meteoroids too small to cause any mechanical damage have been shown to produce unwanted and possibly damaging electrical effects [1]. The electrical effects of these low mass impacts are further primed and exacerbated by different spacecraft charging states that satellites can experience. To characterize the electrical hazards from low mass meteoroid and space debris impacts ground-based impact experiments were performed at accelerator facilities.

Typical meteoroid and orbital debris populations that satellites can encounter have velocities from 7 to 72 km/s, and can have masses up to micrograms while causing negligible mechanical damage. When these hypervelocity impactors strike the surface of a spacecraft, the impact kinetic energy will be converted into ionization/vaporization energy within a very brief timescale. Thus, a small and dense expanding plasma will be produced around the point of impact in addition to the vapor cloud. The study of hypervelocity impacts can yield valuable information about meteoroid composition, spacecraft protection and anomaly effects due to their impacts, and other planetary science related topics. Researchers have detected strong radio-frequency and optical emissions from the impact [2, 3, 4, 6, 10, 15, 16], and have applied various different optical characterization methods to estimate the temperature and density of the plasma and impact vapor cloud [3, 6, 7].

Characterizing and linking the optical flash to impactor parameters can provide a vital and economic diagnostic tool for understanding the types of impacts a spacecraft can encounter and also the types of impact induced electrical effects it is exposed to. In characterizing optical emissions, both [3, 6] use Planck’s law to model the optical emission as a blackbody for the entire time span after impact. However, the emission spectrum has been observed to evolve from optically thick emission body to an optically thin emission body in the experimental data presented in this paper. Thus, this paper is motivated to investigate the domain in time where blackbody radiation is adequate for the impact flash.

Hypervelocity impact events can be studied via in-situ measurements in space [5] or at ground-based experimen-
tal facilities[3, 6, 10]. Due to the resource availability and cost, the ground-based facilities offers an economical controlled experimental environment for hypervelocity impact studies. To characterize the effects associated with hypervelocity impacts using ground-based experiment, observations from diverse sets of impactor mass and velocity configurations are required. While meteoroids can achieve both large masses and velocities in orbit, ground-based facilities can only maximize one parameter, either mass or velocity, as in Figure 1.

After the plasma plume has been formed it rapidly expands into the vacuum. This plasma acts as the conduit for many of the unwanted and possibly hazardous electrical effects associated with the impact. The interplay between the various spacecraft charging conditions and this plasma can lead to wide-band electromagnetic spectrum emissions, which includes RF and visible optical emission, and act as a catalyst for arc discharges to occur.

2. IMPACT CHARACTERIZATION

During a hypervelocity impact (HIP), the impactor rapidly vaporizes and ionizes itself and a portion of the target resulting in the creation of a small and dense expanding plasma. The state of the resulting plasma plume is dependent upon the constituents of both the impactor and target materials in addition to impactor mass and velocity. The parameters of the impactor can then be probed through the optical emissions that the plasma produces.

2.1. Optical Emissions

The strong optical flash generated by the hypervelocity impact can not only damage the sensitive optical instrument on board the spacecraft, but also be used as a diagnostic tools to relate the electrical damages, the hypervelocity impactor properties, and the impact generated plasma properties. We hypothesize an optical model for the HIP as shown in Figure 2 in order to measure the plasma properties during an hypervelocity impact event.

In this model, the optical emission in the early expansion phase is dominated by the continuum emission and can be closely approximated as a radiating blackbody. The continuum brightness temperature of the plasma can be estimated directly using the Plancks law as shown in Eq.1, where $I$ is the spectral radiance of the body in $Wsr^{-1}m^{-2}kg^{-1}s^{-1}K^{-1}$, $\lambda$ is the wavelength, $k$ is the Boltzmann constant $(1.38 \times 10^{-23} m^2kg^{-1}s^{-2}K^{-1})$, $T$ is the equilibrium temperature in Kelvin, $c$ is the speed of light, and $h$ is the Planck’s constant $(6.626 \times 10^{-34} m^2kg^{-1}s^{-1})$.

$$ I(\lambda, T) = \frac{2\pi c^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k T}} - 1} $$ (1)

As the plasma expands, the continuum emissions begin to decay and the line emissions will stand out. The plasma properties in this intermediate expansion regime can be estimated using the ratio between the continuum and line emissions. These two expansion phases can also be related to the conditions in the impact plasma.
Figure 3. Optical Evolution High Speed Images: The high speed images from AVGR experiment show the impact flash transition from optically thick to thin.

Figure 4. The continuum plasma temperature measurement in early expansion phase.

In the early expansion plasma, it is non-ideal and collisional. Thus, it exhibits local thermal dynamic equilibrium (LTE) and gives an optically thick continuum-dominant emission presentation. The plasma in the intermediate expansion phase transitions into an ideal and collision-less plasma. As the continuum emissions weaken, the atomic/molecular line emissions dominate in this optically thin plasma. This hypothesis is supported by the impact flash images taken at AVGR as shown in Figure 3, and the Planck law fitting in Figure 4. In this paper, we will focus on the early expansion phase of the impact plasma emission spectrum via Planck’s law.

2.2. RF Emissions

High power RF emissions can induce damaging currents in sensitive electronics and can create disturbances in nominal sensor behavior and performance. In this paper we explore the how the production of RF emissions from impact events evolves as a function of spacecraft potential. One source of RF emission from impacts can occur from a bulk acceleration of electrons in negatively biased spacecraft. After the impactor vaporizes and ionizes itself and a portion of its target, all of the liberated electrons are accelerated away from the impact crater due to the electrostatic fields created from the spacecraft’s negative bias. The strength of this emission is proportional to the number of liberated electrons and the spacecraft’s bias. The familiar Larmor formula gives the radiated power of an accelerated charge:

\[ P = \frac{q^4 |E|^2}{6\pi\epsilon_0 c^3 m_q} \]  

where \( P \) is the radiated power in watts, \( q \) is the particle charge, \( E \) is the electrostatic field induced by the targets bias, \( c \) is the speed of light, \( m_q \) is the mass of the charged particle, and \( \epsilon_0 \) is the permittivity of free space. Ground-based tests have shown that the amount of charge liberated by a hypervelocity impact is given by approximately

\[ Q = 0.1m \left( \frac{m}{10^{-11}} \right)^{0.02} \left( \frac{v}{5} \right)^{3.48} \]  

[13] where \( Q \) is the total liberated charge, \( m \) is the mass of the impactor in grams, and \( v \) is the velocity of the impactor in km/s. This RF emission mechanism is significantly weaker in positively biased targets as the acceleration of the ions is many orders of magnitude lower than electrons for the same electric field strength.

An additional possible source of RF emissions from grounded targets is through plasma instabilities with small-scale spatial correlations such as a coherent plasma
sheath oscillation [14], and the Weibel instability [17]. After impact, as the isothermal plasma thermally expands into the vacuum of space a bulk separation occurs as the electrons outpace the ions. This bulk separation induces an internal electric field that starts an oscillation which occurs at the plasma frequency. Along the expanding edge of the plasma the produced electromagnetic fields from this oscillation are allowed to propagate outside of the plasma providing another RF emission mechanism. As the plasma expands and becomes less dense the frequency of this emission decays. The frequency of this oscillation is given as

\[ \omega_p = \sqrt{\frac{n_e e^2}{m_e e_0}} \]  

where \( n_e \) is the number density of electrons, \( e \) is the electric charge of an electron, \( m_e \) is the effective mass of an electron, and \( e_0 \) is the permittivity of free space.

2.3. Arc Discharge

Differential spacecraft charging also poses a risk for spacecraft health in the context of arc discharges induced by hypervelocity impacts. Dielectrics can easily cause different portions of a spacecraft to reach different voltage potentials. Spacecraft can be naturally inclined to achieving different voltage potentials due to their orbit, orientation, surface topography, and on board components. One area where differential voltages are often found is on solar panels. Solar panels and all the other electrical components are designed to avoid a voltage breakdown by providing a large enough spacing between areas of differential biases for the magnitudes of voltages that are expected. However, if a hypervelocity impact were to occur in the vicinity of a differential voltage the resulting plasma plume can act as a conductor between the two surfaces allow for a rapid and dangerous discharge of current across the dielectric.

3. EXPERIMENTS

3.1. Ames Vertical Gun Range

The NASA Ames Vertical Gun Range (AVGR) is a 0.3 caliber light gas gun, which launches projectiles to around 5-7 km/s. The AVGR was used to perform milligram sized impact and arc discharge experiments. The optical and arc discharge data presented in this paper uses a fine grain sand projectile (0.0161 g) which will be accelerated together with the sabot material, and the total mass is 0.3938 g at a velocity of 4.65 km/s. The rest of the impactors are single aluminum impactors packed with nylon sabot material. The complete list of single particle aluminum impactor mass-velocity configurations is shown in Figure 6. Due to the inherent limitations in using light gas guns both the number of impacts and the variance in their masses and velocities is low. The target is a copper plate which can be charged to various potentials to represent different spacecraft charging surface conditions. For single particle shots the impact angle is at 30 degrees from the normal, and for the fine grain sand shot at 0 degrees from the normal. The chamber pressure is set to be at 0.71 torr, which presents a neutral-rich environment for the impact generated plasma when compared to the high vacuum provided by CCLDAS facility. The AVGR facility and the inside chamber setup of the sensor suite is depicted in Figure 5. The beam path is set to be perpendicular with the line of sight of the optical sensor suites, which are focusing onto the target from outside the chamber. (The optical sensors are placed outside the chamber to minimize the debris damage on the sensor, whereas the RF sensors are located inside the chamber.) The optical sensor is shown in Figure 7.

Figure 5. NASA Ames Research Center Ames Vertical Gun Range (AVGR) Test Facility Setup. The AVGR gun is in its vertical position shown in the left figure, and the sensor setup in the chamber is shown in the right figure. As seen from the diagram, the projectile beam path is perpendicular to the line of sight of the optical sensors.

Figure 6. AVGR and CCLDAS Impactor Masses and Velocities

In the AVGR experiments, the goal is to characterize the impact plasma that was produced, the electromag-
netic emissions in the visible spectrum (400-700 nm), and the electromagnetic emissions in the RF spectrum (100 to 1000 MHz). An inclined copper target was placed in the center of the chamber and was biased to different voltages to simulate different spacecraft charging conditions. To perform the optical measurements a suite of colored band-passed photomultiplier tubes (PMT) (Hamamatsu Inc., HC-124, 8MHz head-on photomultiplier tubes) and photo-diodes (Pacific Silicon Sensor PS100-6-CER-2, 10 mm²) were used in conjunction with a few high speed cameras (1MHz; Shimadzu HPV-1, Phantom V10, and Phantom V12). The PMT color-filters are centered at 450nm, 550 nm, and 600 nm with 40 nm bandwidth (CVI Laser Optics, F40-450.0-4-25.0M, F40-550.0-4-25.0M,F40-600.0-4-25.0M). The colored band-pass filter and PMT combination will enable a high speed photometry unit to measure the visible spectrum of the impact flash. The data from the photometry sensors are collected by the high speed oscilloscope at 1GHz (TeleDyne-Lecroy, WaveRunner 6Zi) after proper amplification and conditioning through in-house circuit. These sensors were positioned outside of the chamber and made their observations though an optical view port. This configuration is shown in Figure 7. A anti-reflective shroud will be used a beam dump to avoid back scattering of photons. To perform the RF measurements 3 patch antennas centered at 160, 315, 916 MHz were placed inside the chamber one meter away from the target at a 90 degree angle from the plasma expansion path. To characterize the plasma plume generated from the impacts a retarding potential analyzer (RPA) and a transient potential analyzer (TPA) were utilized.

3.2. Colorado Center for Lunar Dust and Atmospheric Studies

The Colorado Center for Lunar Dust and Atmospheric Studies electrostatic accelerator facility is shown in Figure 8. The entire system is oil-free and can be pumped down to high vacuum of $10^{-6}$ torr. As shown in Figure 8, the impact takes place in the large experimental chamber, which is mounted at the end of the beam line. Picogram to femtogram sized iron particles where accelerated at speeds from 15 km/s to 100 km/s and impacted into tungsten targets in high vacuum. Impacts were performed at a variety of target potential conditions ranging from -1000 V to +1000 V to simulate different spacecraft charging conditions. The particle sizes are many order of magnitude less massive than the ones in AVGR as seen in Figure 6.

During this experiment 3095 impacts were observed. To characterize the impact event a multi-physics platform was deployed to capture RF, optical, and plasma emissions at a distance of 10 cm from the impact site. The multi-physics sensor suite is displayed in Figure 9. To perform RF measurements an array of 12 165 MHz patch antennas, two 315 MHz patch antennas, and two 916 patch antennas were used to provide spatial and frequency bandwidth coverage. Three RGB bandpass filtered photomultiplier tubes were used to make plasma temperature measurements, and an all wavelength optical
photodiode tube was used to provide calibration and time of impact data. Plasma measurements were collected on a transient plasma analyzer (TPA) and a retarding potential analyzer (RPA).

4. RESULTS

Through sampling impact events from both extremes of the possible impactor mass/velocity combinations a more complete picture can be drawn about the electrical and diagnosable effects associated with low mass meteoroid and space debris impacts. While the combination of electrostatic accelerator and light gas gun facilities cannot produce the high mass, high velocity configuration that impactors can achieve in orbit, they provide a starting point for a scalability analysis.

4.1. RF Emissions

RF emission signatures were observed during impacts at both CCLDAS and AVGGR facilities. While the effects of the large neutral particle population in the AVGGR facility on RF production still needs to be understood, RF bandwidth emissions were observed in grounded, positively biased, and arc discharge test cases at the AVGR facility. The 315 MHz patch antenna response to a grounded target impact is shown in Figure 10. A strong wide band response is seen a few nanoseconds after impact. Additional pulses are observed in the following microseconds possibly corresponding to secondary impacts from ejecta. In the positively biased impact case there was no RF pulse observed directly after the time of impact, but there were several pulses in the following microseconds that exhibited the same distribution as was seen in the grounded case. Unfortunately, the data acquisition system misfired on the negatively biased target, so no information is available on RF emissions from negatively biased targets at AVGR.

At the CCLDAS facility low power RF pulses were consistently observed 50 nanoseconds after impact in negatively biased targets. The strength of these low power emissions scale with impactor mass and velocity suggesting that in the high mass/velocity impactor configurations the emissions have the potential to become hazardous. Due to the high noise environment and low expected power of emissions from grounded and positively biased targets no emissions were observed in the unprocessed data from CCLDAS.

4.2. Arc Discharge

Two plates were charged with a 400V differential potential between them to simulate adjacent solar panels. The plates were mounted on a dielectric slab and were separated by 1 mm. A fine grain sand was shot to ensure a particle would impact the gap between the differentially charged plates. Figure 12 displays the all wavelength PMT response in conjunction with the measured voltage differential between the plates and the calculated current flow. Within 5-7 microseconds after impact as observed using the PMT response, the expanding plasma begins acting as a conductor between the differentially charged plates allowing them to discharge. Over a 10 microseconds span an 190 V drop was observed in the differential potential as the plasma allowed current to flow between the plates. During a period of the discharge the differential bias goes negative, which could cause brownouts and other possible damages. A large time constant the voltage divider setup masks the more transient nature of this discharge. A potential consequence of this is that the peak voltage and current differentials could be much higher. Accompanying the arc discharge is a wideband RF pulse.

4.3. Optical Characterization

The proposed hypervelocity impact flash evolution shown in Figure 2 is found to be consistent with the high speed images captured during the experiment as shown in Figure 3. A continuum dominant section can be identified in the early phase of the optical evolution shown by the high speed images in Figure 3. The spectrum in the later phases becomes optically thin, and thus deviates from the blackbody model as expected in the hypothesized optical model. For the continuum dominant regime, we have been able to measure the plasma continuum temperature as shown in Figure 4. The spectral emission in the first 40 μs after the impact follows the blackbody radiation model quite well, but the emission spectrum deviates from the Planck's law radiation model after this time. Thus, the first 40μs is roughly the continuum dominant regime for the AVGR experiment. The blackbody continuum model can thus generate an estimate of thermal brightness temperature as a function of time. Addition-

Figure 10. The figure displays the results from the 315 MHz antenna of a ground target impact, and the PMT response as a time of impact fiducial. The dashed black line represents the time of impact.
Figure 11. The figure displays the results from the 315 MHz antenna of a 50V positively biased target impact, and the PMT response as a time of impact fiducial. The dashed black line represents the time of impact.

Figure 12. The to figure is the PMT response which is used to determine time of impact. The second figure is the measured voltage differential between the target plates, and the third figure is the computed current flow.

ally, we can leverage the high speed cameras, which have isolated Red/Blue/Green pixels to acquire a spatially resolved plasma temperature measurement as shown in Figure 13. The isolated Red/Blue/Green pixels of the high speed camera provide spatially resolved relative color ratio measurements. Since the initial impact flash is spatially confined to a small region, we can use the absolute color ratio and temperature measurements acquired by the photometry PMTs to scale the relative color ratio from the high speed camera to gain a spatially resolved temperature measurement of the impact flash. As shown in Figure 13, the high temperature initial expansion front expands outward in the continuum temperature map, which is consistent with the expected radiation pattern predicted by the model [9].

We have also found positive correlation of the continuum plasma temperature and the scaled impactor energy, i.e. $E^{0.64}v^{-2.74}$, as shown in Figure 14, which is consistent with the previous charge production power law [11]. In the preliminary studies, the temperature is strongly correlated with the scaled energy in certain energy range, i.e. the solid trend-line presented in Figure 14. The continuum blackbody temperature can be calculated using either blue and green PMT (i.e. 450 and 550 nm) or blue and red PMT (i.e. 450 and 600 nm). If the spectrum is close to an ideal blackbody, the temperature estimation from the two color ratios will be close. Thus, the deviation of the temperature estimation using two different color ratio is an indicator of the deviation of the visible spectrum from blackbody radiation. The RF emission has also found to have strong correlation with the impactor velocity. Thus, the RF emission takes on strong correlation with the continuum plasma temperature. This is quite an exciting finding since this result enlightens the connection between the RF emission, plasma generation, and impact flash directly.

Figure 13. Spatial Measurement of the continuum temperature at initial expansion phase for the AVGR data. The red-line presents a cross-section view of the temperature profile as shown in the bottom figure.

Figure 14. Continuum temperature and scaled energy from CCLDAS result. The light blue dash line represents the lower bound of scaled energy where temperatures exhibit a strong correlation with the scaled energy.
5. CONCLUSIONS

This paper demonstrates the successful deployment of a sensor suite to make simultaneous RF, optical, and plasma measurements across a diverse set of impact conditions. Measurements were taken at the light gas gun facility at AVGR and the electrostatic accelerator at CCLDAS to provide the most comprehensive picture available in ground based facilities. The simultaneous multi-sensor approach is crucial to mapping out a time history of the plasma. It was observed that the electrical effects induced by impact are a function of the spacecraft’s current charging condition. Experiments at AVGR demonstrated how the impact plasma can induce arc discharges in differentially charged systems. RF emissions were observed under multiple spacecraft charging conditions and at both electrostatic accelerator and light gas gun facilities. The scaling of RF emission power with impactor mass and velocity that was observed at CCLDAS suggests that high mass, high velocity impacts that can be seen in orbit have the potential to become hazardous. The observed optical emissions generate a time-resolved continuum plasma temperature measurement using high speed photometry sensors, and a spatially resolved continuum plasma temperature measurement when high speed camera is used in conjunction. The electromagnetic signals, including RF and optical emission, are also captured during the arc discharge event induced by differentially charged target surface, which simulates that the hazardous differential charging conditions on many spacecrafts. Strong correlations between the optical emission and the RF emission have been detected, which can be a promising detection method for future characterization of spacecraft electrical damages from meteoroids using optical and RF measurements.

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