Radio-Frequency Emissions from Hypervelocity Dust Scale Meteoroid Impacts

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Objective

This research seeks to characterize the hazardous electrical effects produced by dust-sized meteoroid impacts with spacecraft, and to assess the role that ionospheric conditions play in the evolution and emissions of the impact plasma.

Motivation

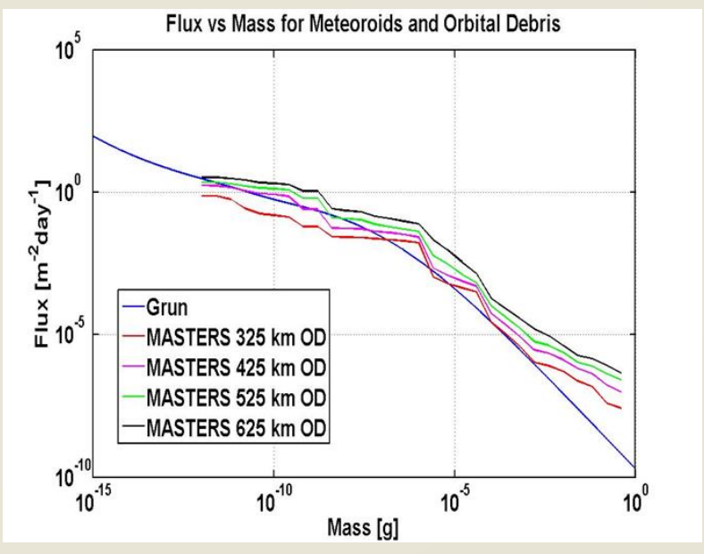


Figure 1. Meteoroid Flux Models [1]

[1] Gurnett, D. and Team, C. 2004. Initial results from the Cassini radio and plasma wave science investigation at Saturn. 35 p. 1895.

The space environment, which includes both solid and energetic particles as well as electromagnetic radiation, poses many hazards to spacecraft. Historically, impacts by solid particles, including meteoroids, has primarily been linked to mechanical damage. However, recent research has shown that meteoroids with masses too small to cause significant mechanical damage have the potential to still generate damaging electrical effects. Because these particles are far more numerous (Fig. 1), the probability of impact is much greater.

Introduction

When impacts occur at speeds faster than the target's speed of sound they are referred to as hypervelocity impacts. In this case the impact site and meteoroid are vaporized and ionized, producing a dense plasma that expands into the vacuum of space. This impact plasma is the conduit for many of the unwanted electrical effects associated with impact.

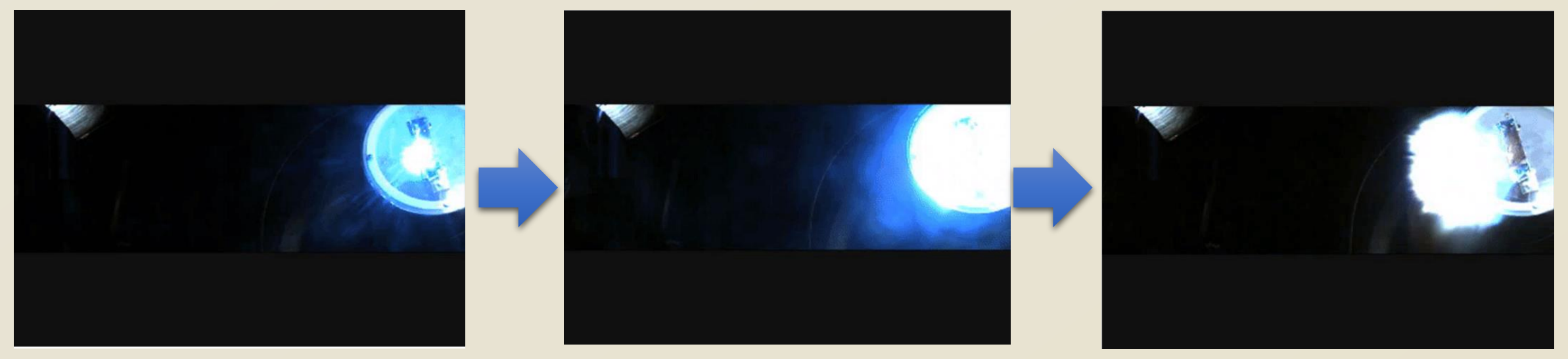


Figure 2. Impactor vaporizes and ionizes and expands into vacuum.

Strong RF pulses generated from impact plasma have the potential to induce damaging currents in sensitive electronics and can create disturbances in nominal sensor behavior and performance. Emissions can stem from different phenomena depending upon spacecraft charging conditions.

While the high mass and velocity impact conditions that satellites in orbit can experience cannot be recreated on the ground, a range of lower energy impacts can be recreated using light gas gun and electrostatic accelerator facilities. To isolate the low-power emissions from impact, a signal processing technique called Prior Constrained Source Separation (PCSS) was developed.

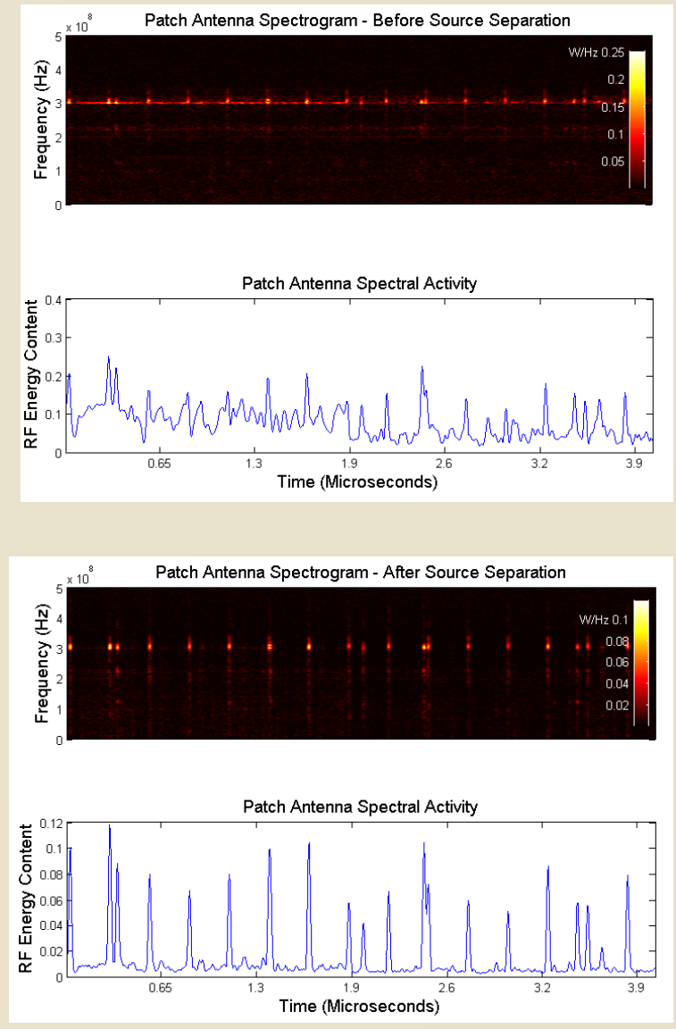
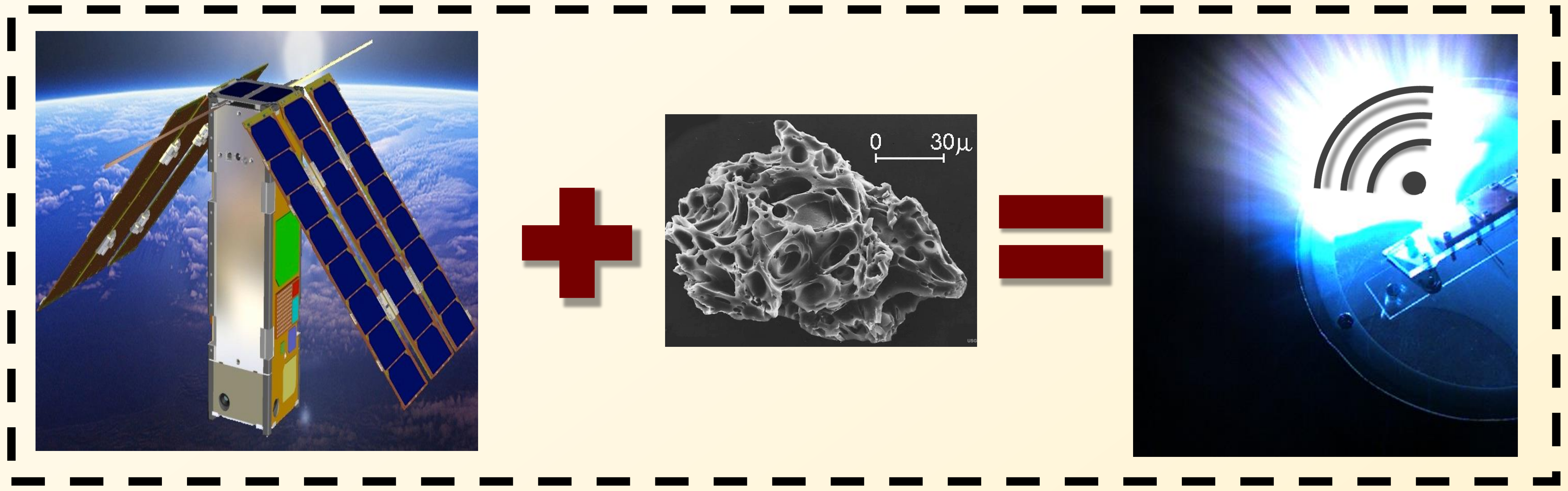


Figure 3. PCSS Noise Excision



Effects of Space Weather on Impact Phenomena

The evolution of the impact plasma is governed by the boundary conditions imposed by the background plasma environment and subsequent spacecraft charging condition. Solar events and ionospheric storms have the ability to affect plasma densities and temperatures that spacecraft are exposed to, potentially making them more susceptible to electrical damage resulting from meteoroid impacts.

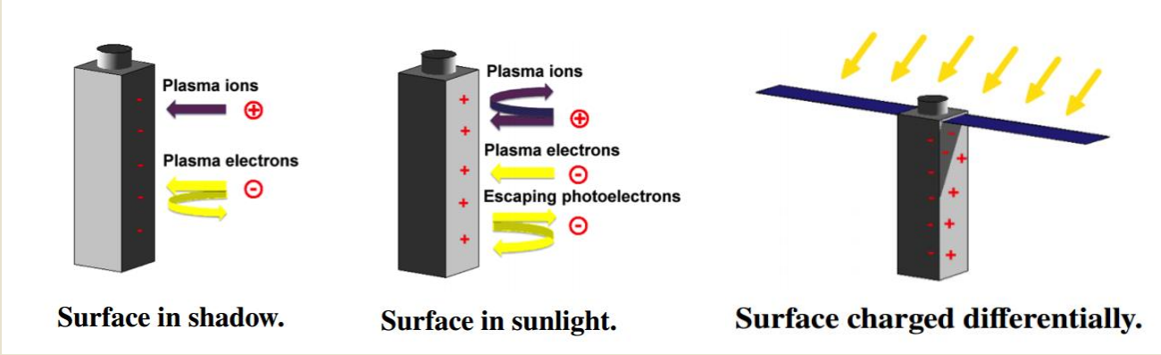


Figure 4. Space weather events can drive spacecraft charging conditions.

Bulk Particle Acceleration

A spacecraft that has accumulated a potential bias relative to the background plasma produces RF emissions from accelerating the impact plasma.

Sheath Oscillations

The impact plasma expansion on unbiased satellites is thermally dominated and oscillations in the plasma sheath couple to propagating RF waves.

Arc Discharges

The impact plasma can act as a conductor between differentially charged portions of a spacecraft inducing a potentially damaging arc discharge and RF emission.

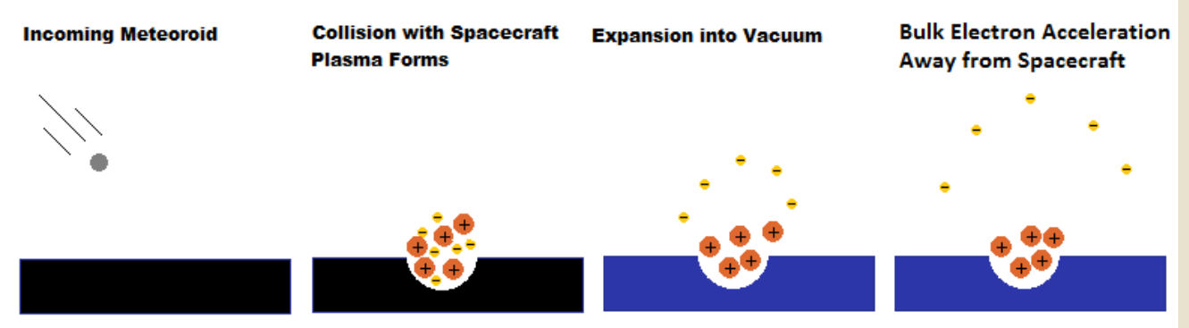


Figure 5. Bulk Particle Acceleration

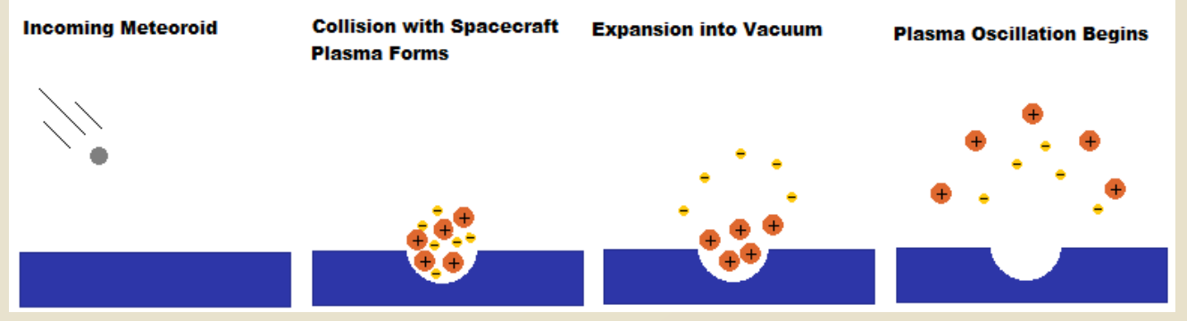


Figure 6. Plasma Sheath Oscillation

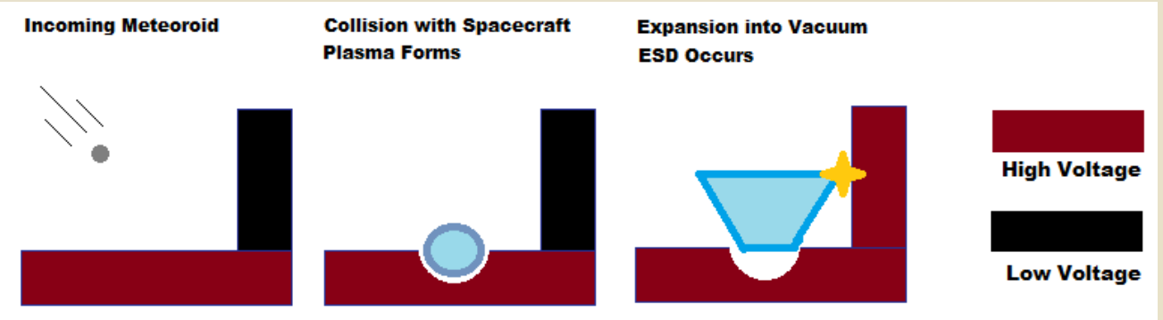


Figure 7. Arc Discharge

Experiment Campaign

Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS)

Femtogram to pictogram iron particles were impacted into a tungsten target at 15-100 km/s. To simulate the space environment, the impacts occurred in a high vacuum (10^{-6} Torr), and the target was given bias potentials from -1000 V to 1000 V to simulate natural spacecraft charging conditions. To characterize the impact plasma and the electromagnetic emissions the sensor suite shown in Figure 10 was used.

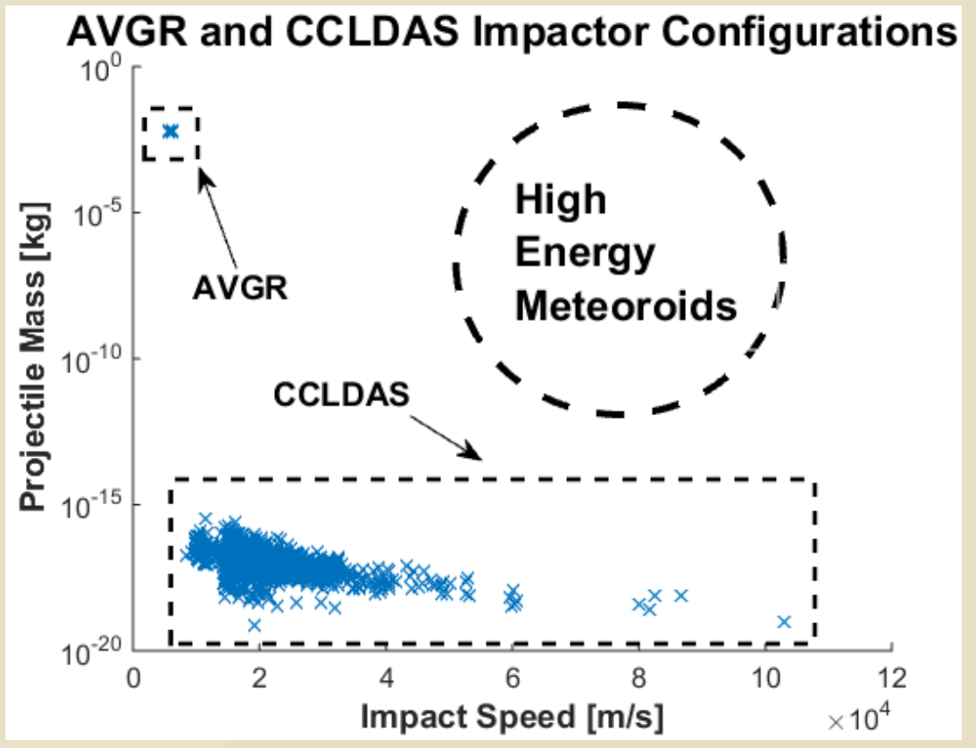


Figure 8. Impactor Mass and Velocity

Ames Vertical Gun Range (AVGR)

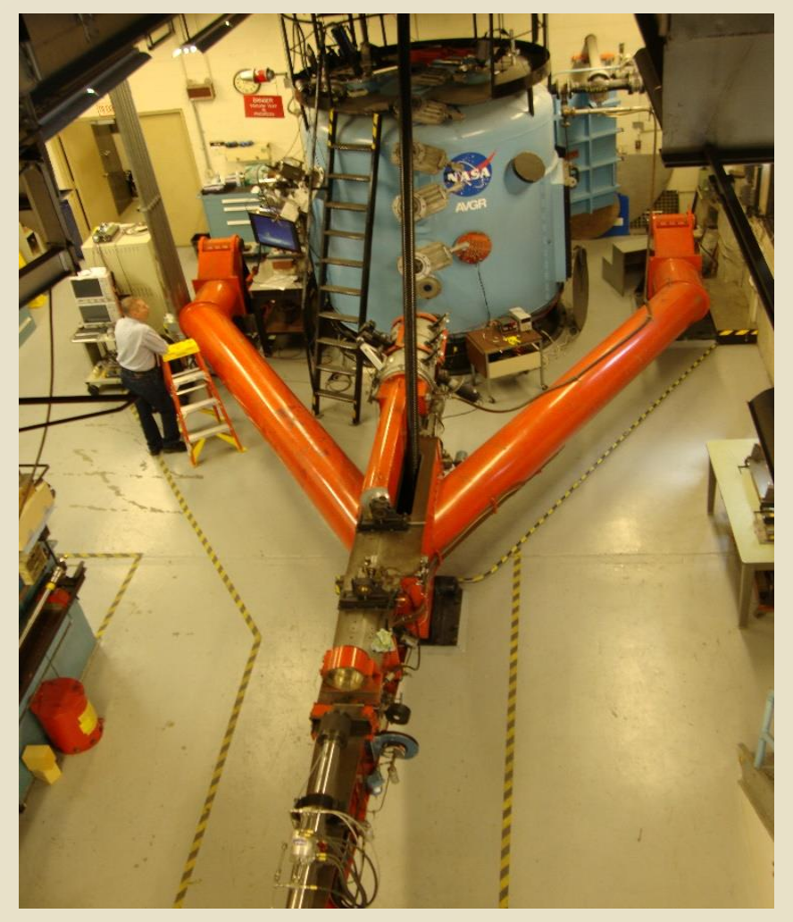


Figure 9. AVGR

A set of impacts were performed at AVGR to capture the high mass low velocity portion of the impactor spectrum. Milligram-sized iron particles were impacted into copper targets in 0.71 Torr vacuum. Data was collected on high-speed cameras, MHz spectrum patch antennas, plasma sensors, and optical wavelength photomultiplier tubes.

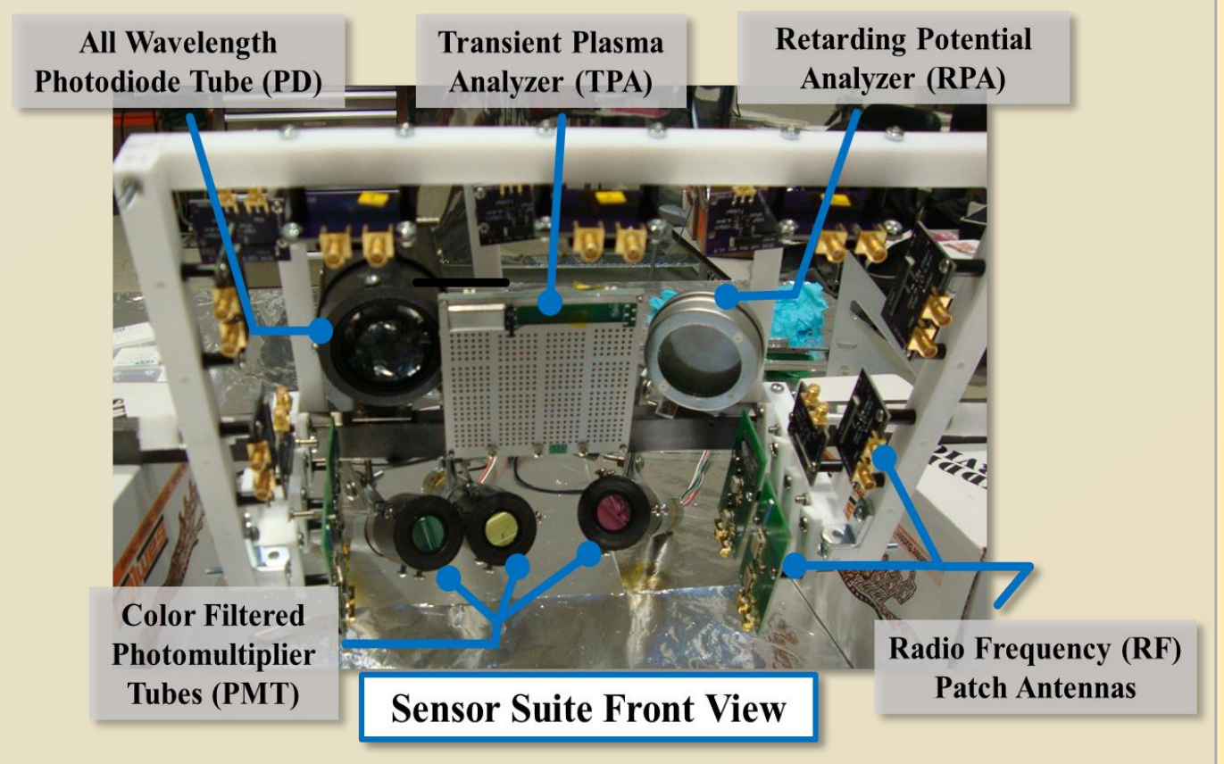


Figure 10. CCLDAS Sensor Suite

Results

CCLDAS – Results

Wideband RF pulses were observed ~50 ns after impact in cases where the target was negatively biased. These results further corroborate results previously obtained at the Max Planck Institute (MPI). These emissions are the result of a bulk acceleration of the liberated electrons. The power of these emissions is given by the Larmor formula,

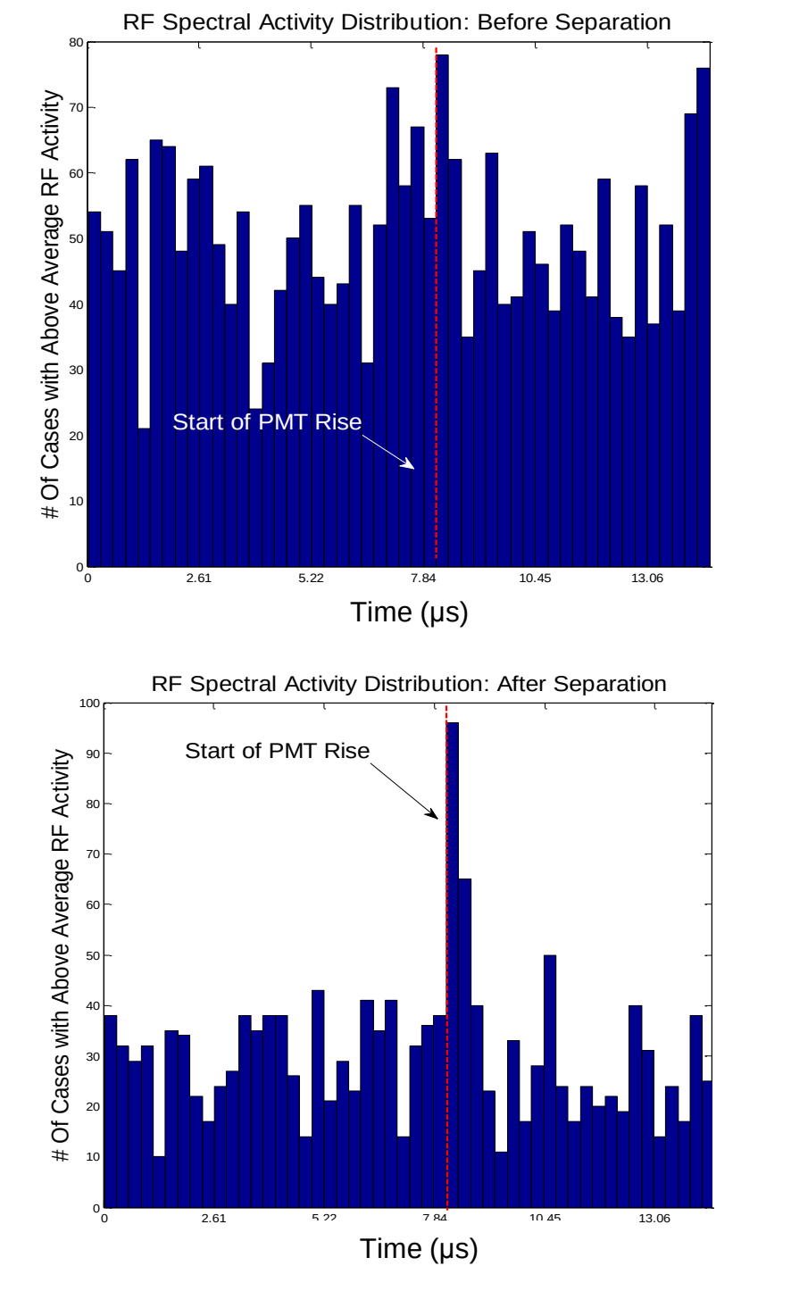
$$P = \frac{Q|q^3|E^2}{6\pi\varepsilon_0 c^3 m_e^2}$$

where Q is the liberated charge, given by the empirical formula

$$Q = 0.1m\left(\frac{m}{10^{-11}}\right)^{0.02}\left(\frac{v}{5}\right)^{3.48} \quad [2]$$

Post PCSS Detection

PCSS filtering greatly increases the detection of impact generated RF pulses.



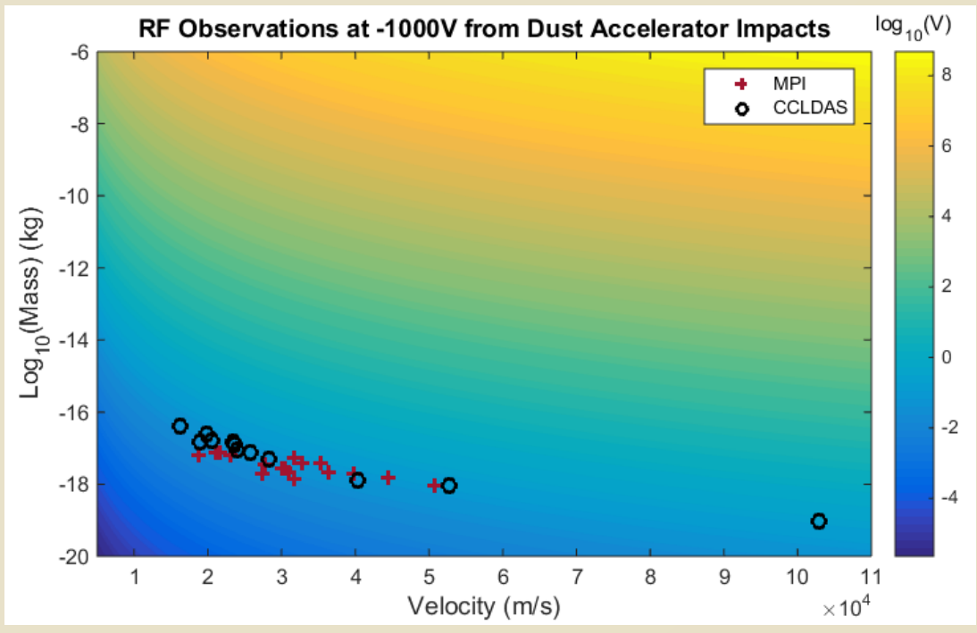


Figure 11. RF Emission Scaling

Observed Scaling

An RF emission scaling law was derived using results from MPI and CCLDAS. A Monte Carlo simulation was conducted to obtain error bounds.

$$Peak\ RF = Am^{0.9\pm0.6}v^{3.9\pm1.5}$$

The derived scaling law indicates that RF emissions can become hazardous at high mass and velocity impacts.

AVGR – Results

While the effects of the neutral-rich environment at the AVGR facility are still unclear, wideband RF pulses were observed under multiple target bias conditions. A strong wideband pulse was observed within nanoseconds after impact with several weaker, longer duration emissions in the following microseconds on grounded targets. Impacts were also able to produce arc discharges and RF pulses.

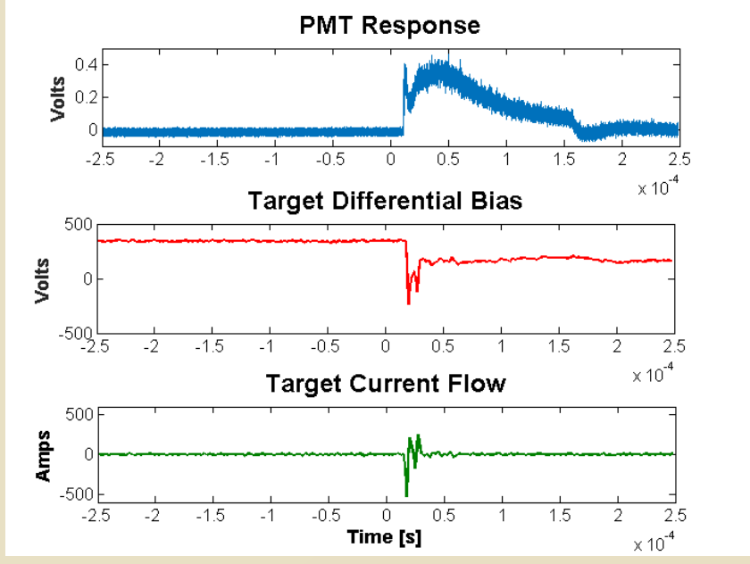


Figure 12. Arc Discharge

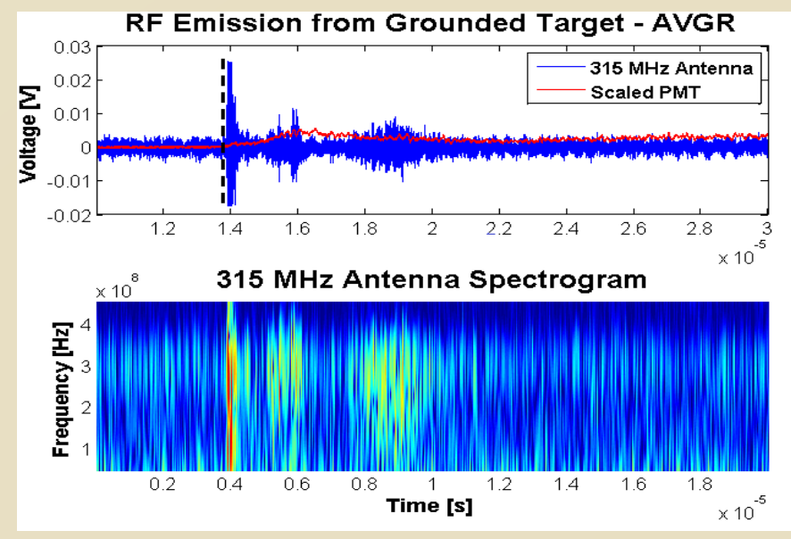


Figure 13. Grounded RF emissions.

[2] McBride, Neil, and J. A. M. McDonnell. "Meteoroid impacts on spacecraft: sporadics, streams, and the 1999 Leonids.". Planetary and Space Science 47.8 (1999): 1005-1013.

Acknowledgements

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