Dusty Plasma Effects in Hypervelocity Impacts

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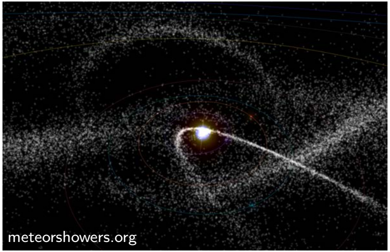
Meteoroids and space debris

- Hypervelocity impacts routinely occur in space.
  - Velocity greater than material speed of sound $\rightarrow$ hydrodynamic behavior.
  - Caused by micrometeoroids and orbital debris (MMOD).

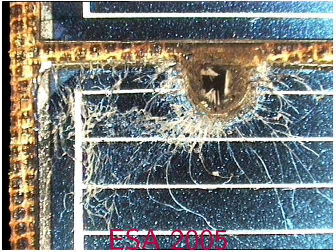


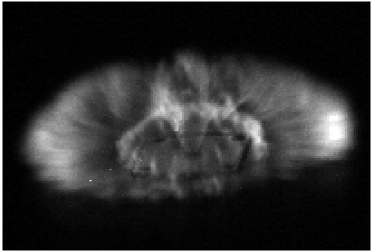
- **Meteoroids & dust**: 11–72 km/s.
- Throughout the solar system.

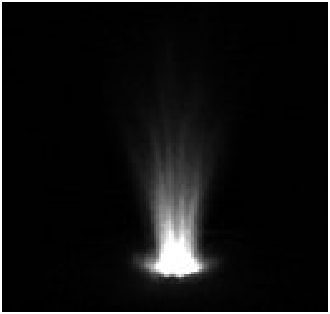
- **Space debris**: 7–11 km/s.
- Concentrated in low-Earth orbit (LEO).

Risk to spacecraft

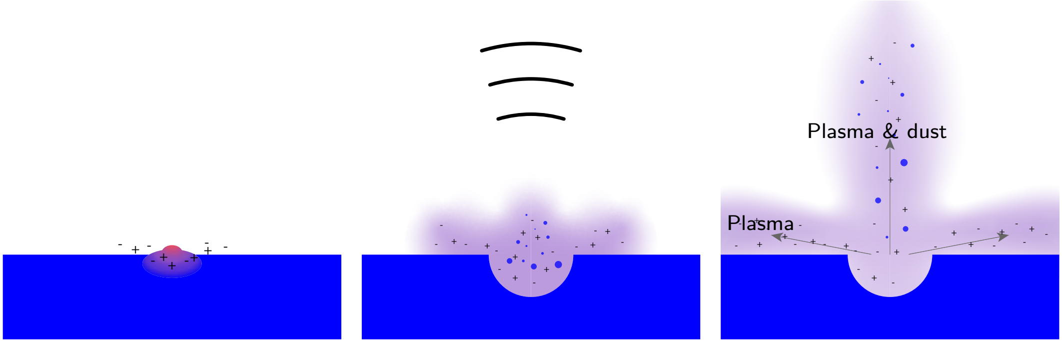
- Mechanical damage from large impactors.
  - May be catastrophic if critical components hit.
- Electrical damage from impact plasma.
  - Potential for damaging EMP and RF emission.







Impact Process



Crater Formation
Jetting

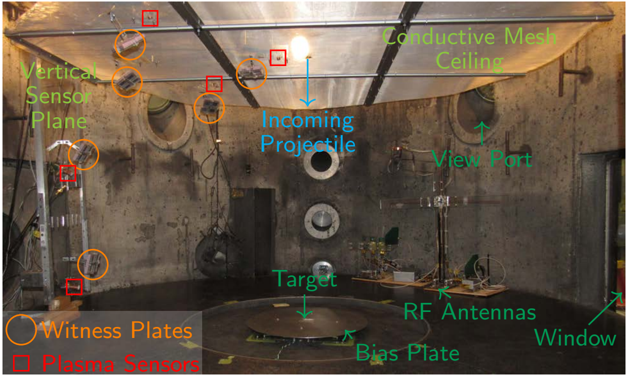
Initial Expansion
Dust Charging
Electromagnetic Radiation

Charge Separation

Research questions

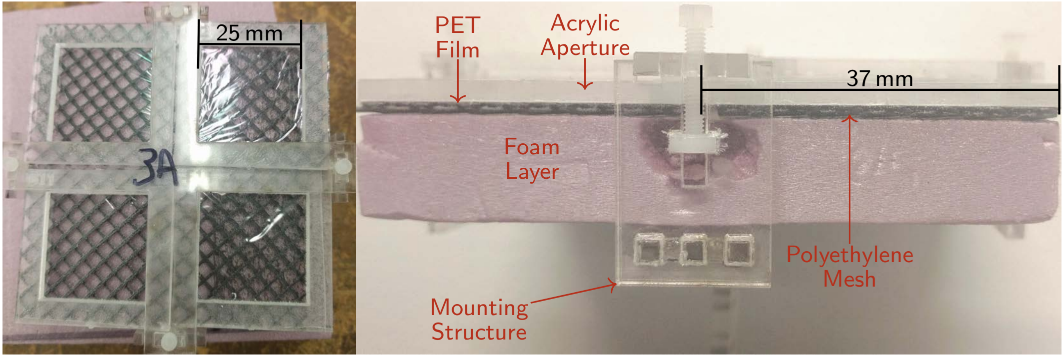
1. What are the characteristics of the ejected material?
2. How do we model dust charging and dynamics?
3. How does dust affect the expanding plasma and associated measurements?

Light gas gun campaign

- 13 shots at NASA Ames Vertical Gun Range (AVGR) in early 2019, ~5 km/s.
- Varied target material and bias, including aluminum and regolith simulant.
- Optical, RF, plasma, and dust measurements.

Witness plate design

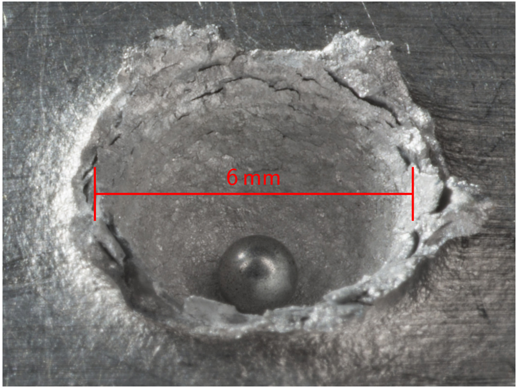


- Thin PET (Mylar) film witness plates to characterize microscopic debris.
- Multiple thickness films 1–15 μm, results from 1 μm films.

Impact observations

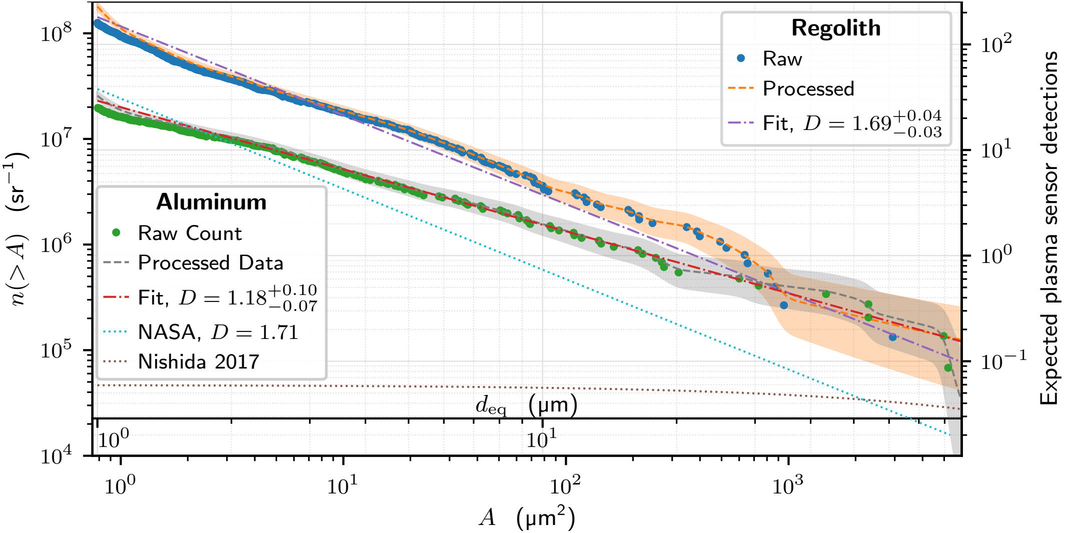
- Aluminum debris ejected in thin conical sheet $\sim 30^\circ$ from vertical.
- Regolith ejected in cone around vertical with $\sim 20^\circ$ half-angle.

Impact observations

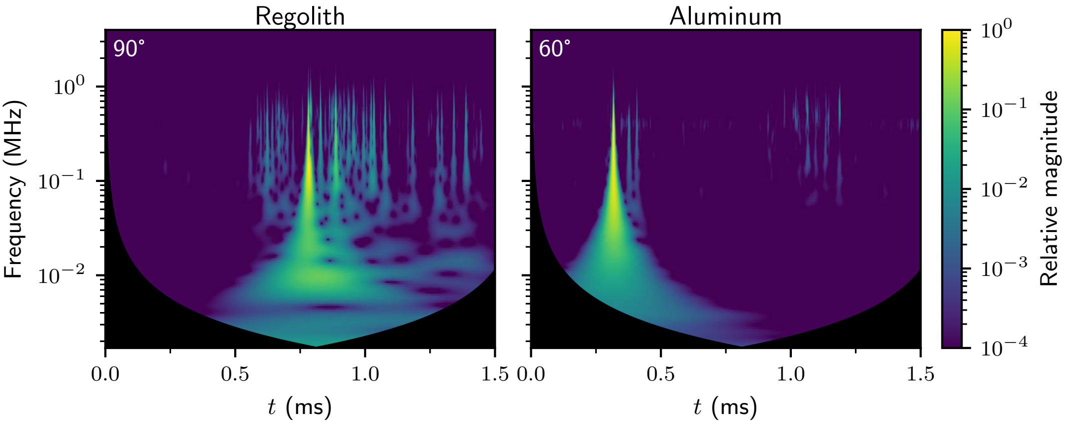


- Aluminum debris ejected in thin conical sheet $\sim 30^\circ$ from vertical.
- Regolith ejected in cone around vertical with $\sim 20^\circ$ half-angle.
- $\sim$400x (by mass) material ejected from regolith target compared to aluminum.

Particle size distribution (in region of peak flux)

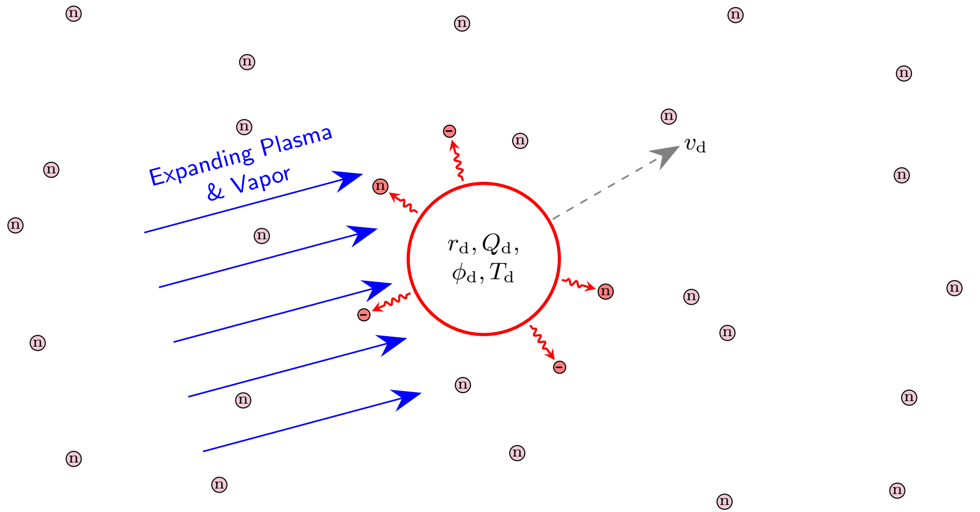


Plasma measurements in debris plume

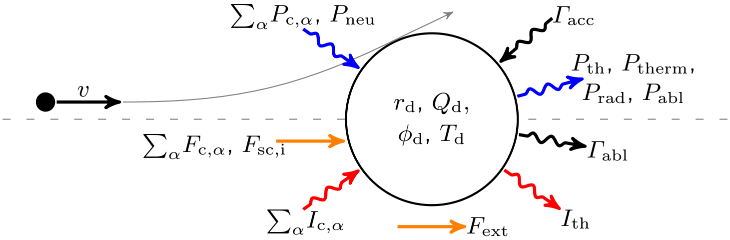


- Thin bands likely indicate dust (impulsive measurement).
- Order-of-magnitude agreement with measured particle size distribution.

Ejecta modeling



Extended OML model



- **Currents**: OML collection, thermionic emission.
- **Forces**: OML collection, Coulomb scattering, external fields.
- **Energy**: OML collection, thermionic emission, blackbody radiation, recombination and thermalization at surface, ablation.
- **Mass**: Accumulation, ablation.

Solution method

- Parameterize (almost) everything using fundamental quantities:

$$u_{\mathrm{i,n}} = \frac{v_{\mathrm{d}}}{v_{\mathrm{ti,n}}} \qquad \mu_{\mathrm{i,n}} = \frac{m_{\mathrm{i,n}}}{m_{\mathrm{e}}} \qquad \beta_{\mathrm{i,n}} = \frac{T_{\mathrm{i,n}}}{T_{\mathrm{e}}}$$

$$\rho_{\mathrm{d}} = \frac{r_{\mathrm{d}}}{\lambda_{De}} \qquad \tau_{\mathrm{d}} = \frac{T_{\mathrm{d}}}{T_{\mathrm{e}}} \qquad j_\alpha = \frac{|I_\alpha|}{4\pi r_{\mathrm{d}}^2 e n_{\mathrm{e0}} v_{\mathrm{te}}} \qquad \varphi_{\mathrm{d}} = \frac{e\phi_{\mathrm{d}}}{kT_{\mathrm{e}}}$$

- Solve $j_{\mathrm{i}}(\rho_{\mathrm{d}}, \beta_{\mathrm{i}}, \mu_{\mathrm{i}}, \varphi_{\mathrm{d}}) - j_{\mathrm{e}}(\varphi_{\mathrm{d}}) + j_{\mathrm{th}}(T_{\mathrm{e}}, \tau_{\mathrm{d}}, \varphi_{\mathrm{d}}) = 0$ for equilibrium potential φ_{d}.
- Evolve position, velocity, temperature, and mass using ODE integration.

$$\dot{r} = v_{\mathrm{d}} \qquad m_{\mathrm{d}}\dot{v}_{\mathrm{d}} = \sum_\alpha F_{\mathrm{c},\alpha} + F_{\mathrm{sc,i}} + F_{\mathrm{ext}}$$

$$m_{\mathrm{d}} c_{\mathrm{p}}(T_{\mathrm{d}})\dot{T}_{\mathrm{d}} = \sum_\alpha P_{\mathrm{c},\alpha} + P_{\mathrm{th}} + P_{\mathrm{surf}} + P_{\mathrm{abl}} \qquad \dot{m}_{\mathrm{d}} = m_{\mathrm{i}}\left(\Gamma_{\mathrm{acc}} - \Gamma_{\mathrm{abl}}\right).$$

Expansion model

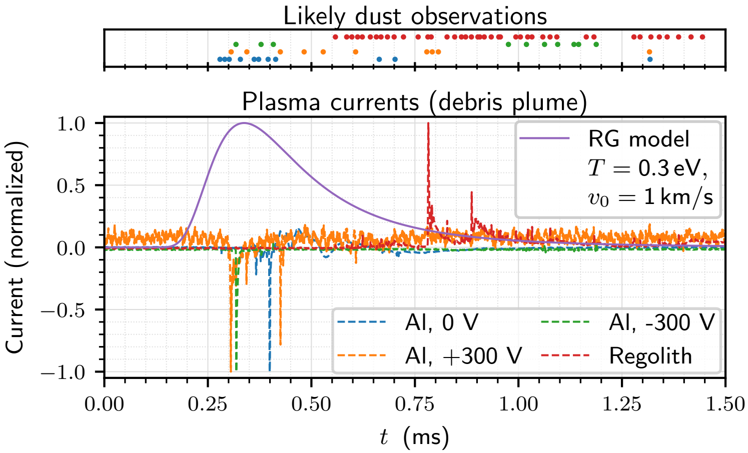
- Renormalization-group symmetry (RGS) for a spherically expanding plasma bunch.
  - Self-similar solution to the Vlasov equation.
  - Function of space *and* time: $f(\boldsymbol{r}, \boldsymbol{v}, t) = f(\tilde{\boldsymbol{r}}, \tilde{\boldsymbol{v}}, 0)$.

$$n_{\mathrm{e}}(r,t) = \frac{n_{\mathrm{e}0}}{(1+\Omega^2 t^2)^{3/2}} \exp\left(-\frac{1}{2}\frac{\Omega^2}{1+\Omega^2 t^2}\left(\frac{r - v_0 t}{C_{\mathrm{s}}}\right)^2\right)$$

$$v_{\mathrm{exp}}(r,t) = \frac{\Omega^2 r t + v_0}{1+\Omega^2 t^2}$$

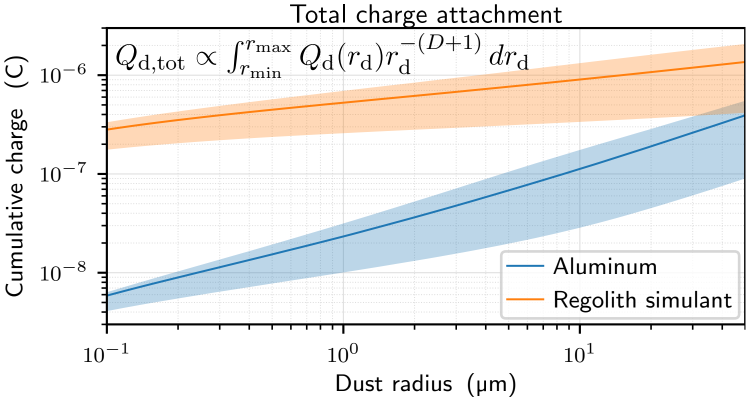
$$n_{\mathrm{e}0} = \frac{Q_{\mathrm{imp}}}{\sqrt{2\pi^3}}\left(\frac{\Omega}{C_{\mathrm{s}}}\right)^3 \qquad \Omega = \underbrace{\frac{v_{\mathrm{ti}}}{L_0}}_{\substack{\text{scale length} \\ L_0 \sim r_{\mathrm{c}}}} \qquad \underbrace{C_{\mathrm{s}} = \sqrt{\frac{k_{\mathrm{B}} T_{\mathrm{i}0} + Z_{\mathrm{i}} k_{\mathrm{B}} T_{\mathrm{e}0}}{m_{\mathrm{i}} + Z_{\mathrm{i}} m_{\mathrm{e}}}}}_{\text{acoustic speed}}$$

Comparison with plasma measurements



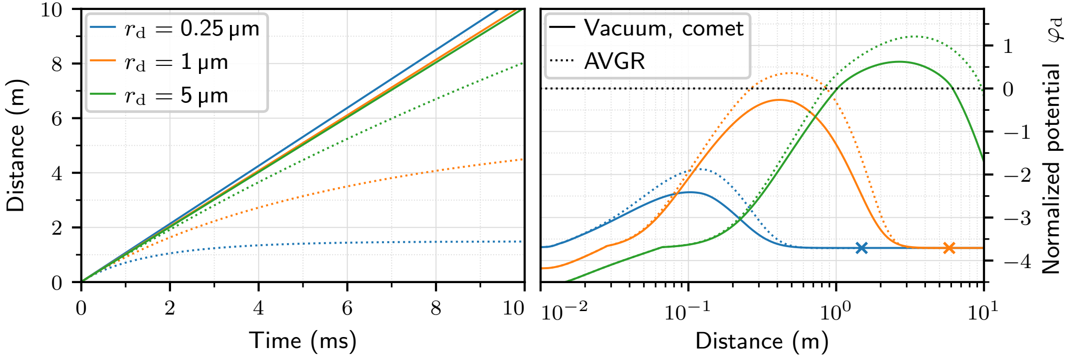
- RGS qualitatively captures plasma observations (for aluminum).
- Negative charge observed for aluminum, positive for regolith.

Initial charge attachment



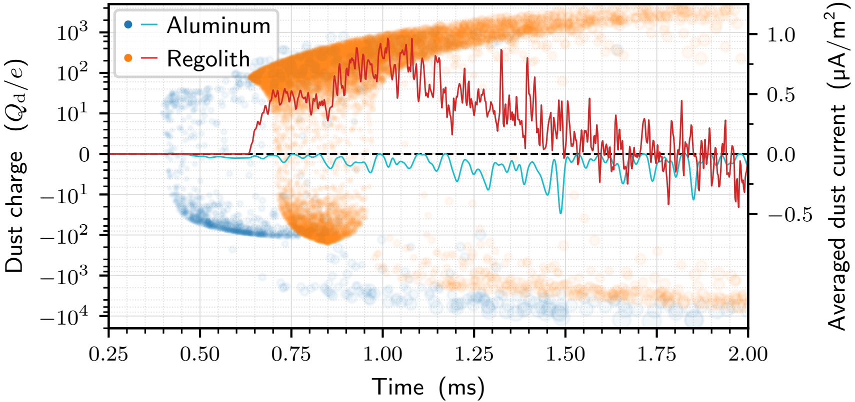
- ∼0.07–1.2 % total electron attachment for regolith, ∼0.02–0.26 % for aluminum.
- Greater depletion in the debris plume → localized dusty plasma effects.

Effect of environment



- 0.5 Torr neutral background at AVGR
  - Affects trajectory – may stop nano-scale debris.
- Neutral background counteracts radiative cooling, slightly higher T_d.
  - Significant increase in thermionic emission ($I_{th} \propto T_d^2 \exp(-W/kT_d)$).

Simulated dust current



- Account for uncertain conditions with a stochastic model.
  - Sample size, initial velocity, and temperature of many dust particles.
- Arrival times and sign of charge qualitatively match experimental observations.

Summary and conclusions

- Measured hypervelocity impact ejecta in a light gas gun campaign.
  - Particle size distributions of microscopic ejecta follow power laws.
  - Predicted count in debris plume agrees with plasma data.
- Developed a dust charging and dynamics model for impact conditions.
  - Extended OML with additional physics to remain valid throughout expansion.
  - Rapid assessment of effects of conditions and parameter uncertainty.
- First quantitative estimate of dust charging in the impact environment.
  - Dusty plasma effects are likely in the debris plume.
  - Impact environment significantly affects dynamics and charge state.
  - Thermionic emission explains observations of positively charged dust.

Acknowledgements

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