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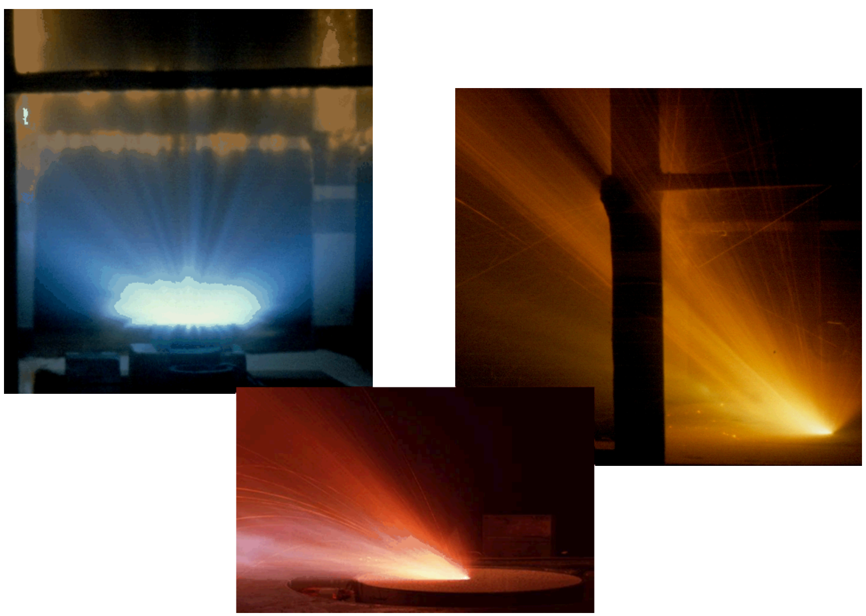

NASA Ames
Vertical Gun Range

Brown University

Computational modeling of electrostatic charge and fields produced by hypervelocity impact

Hypervelocity Impact Symposium
April 27-30, 2015

David Crawford

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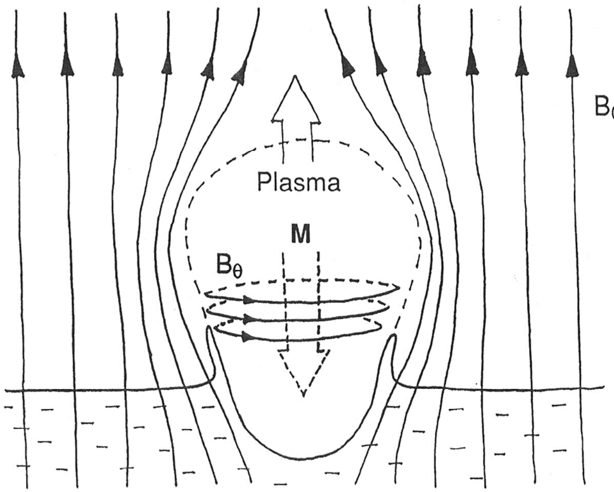
Motivation

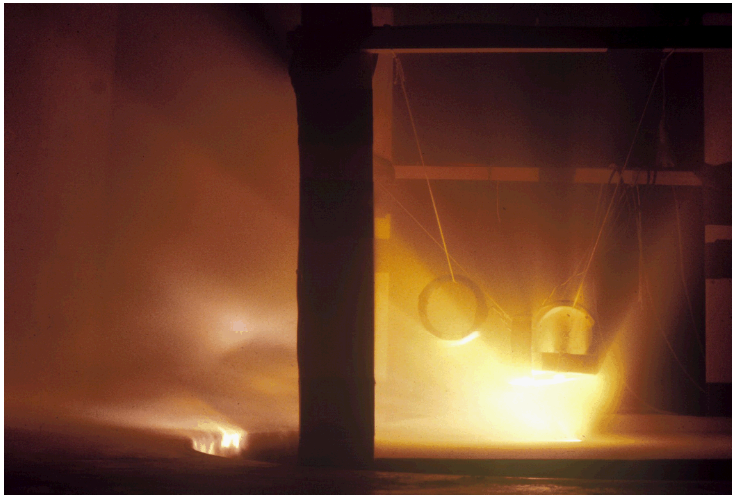
- Lunar, planetary and small body magnetism
- Ejecta motion on small bodies
- Impacts on man-made satellites

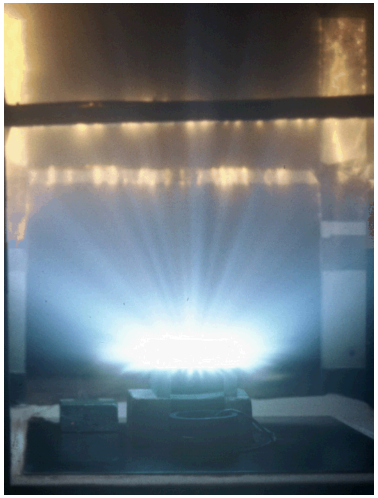


(after Srnka et al., 1979)

AVGR Experiments to Detect Magnetic Fields from Impacts

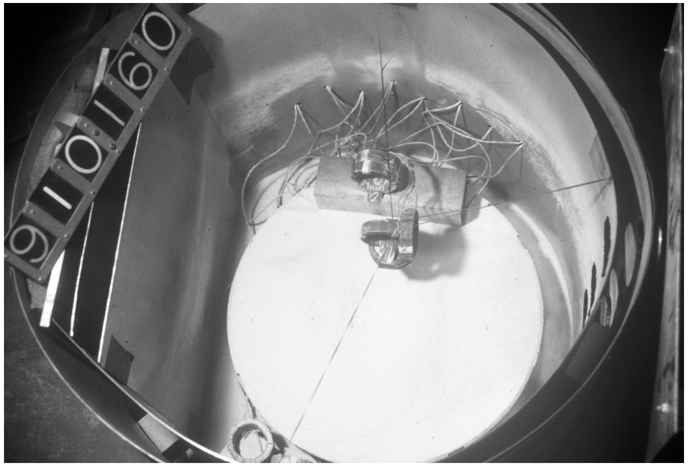
- Magnetic search coils
  - Electrostatic noise eliminated by push-pull design, shielding
- Spontaneous magnetic fields observed
- High ambient magnetic field environment
  - Substantial ambient field contamination

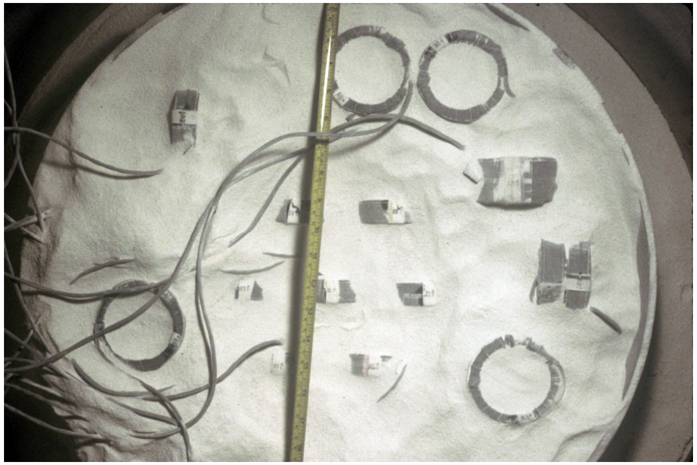




Reduced Ambient Field via Mu-Metal Shield

- Lunar-like ambient field
  - ~450 nT
- Substantially reduced ambient field contamination
- Allowed unambiguous mapping of spontaneous fields



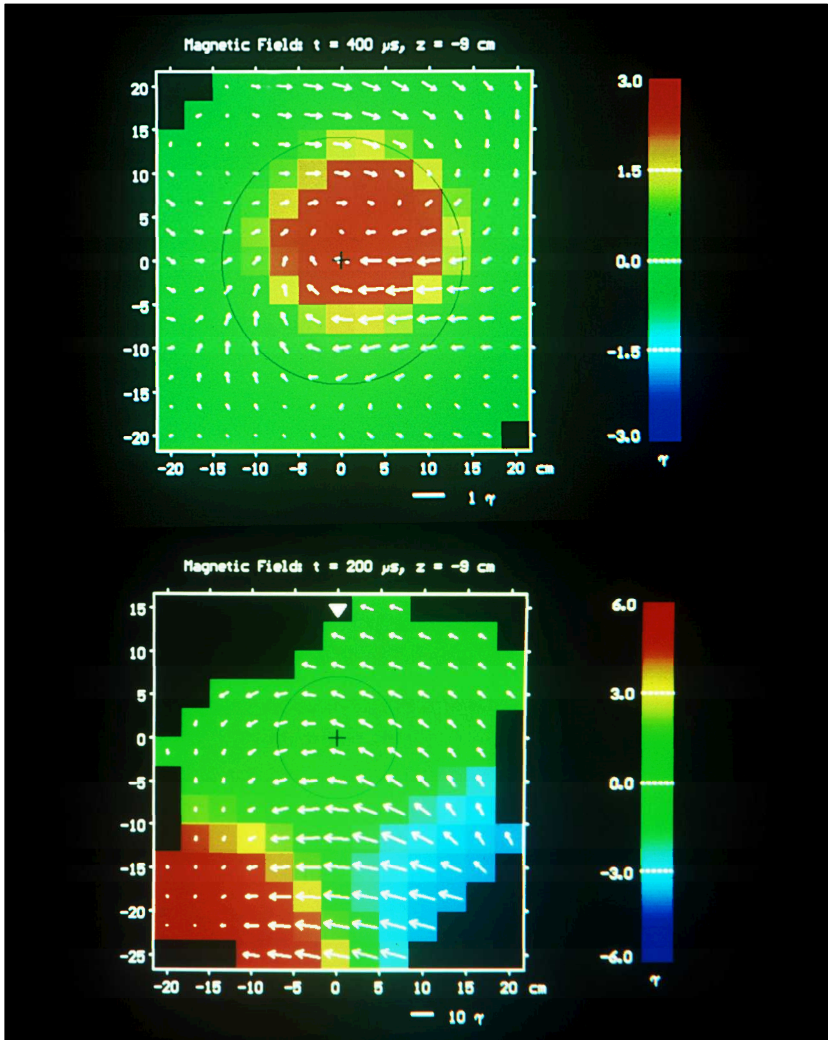


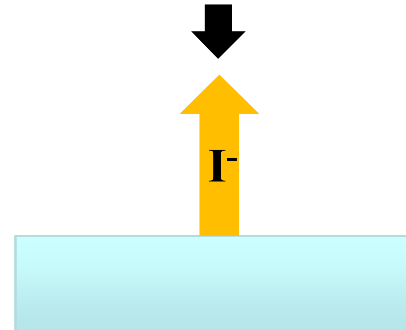
Spontaneous Magnetic Fields from Impacts

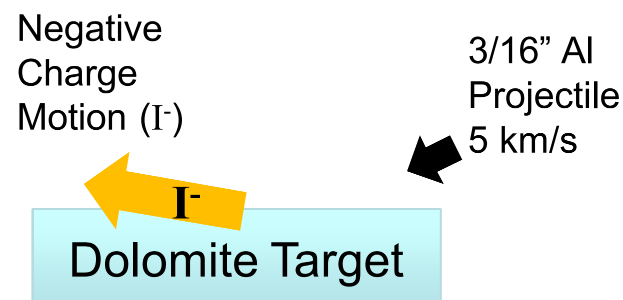
Vector field 9 cm below target surface

Vertical Impact

15° Impact



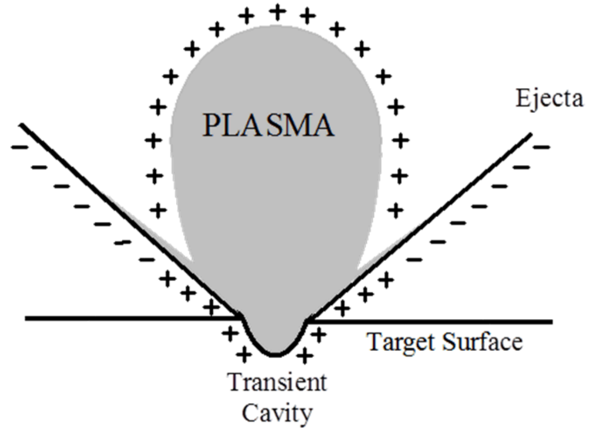




Proposed Mechanism

- Hypervelocity impact produces solid ejecta, melt, vapor, ions and electrons (a dusty plasma).

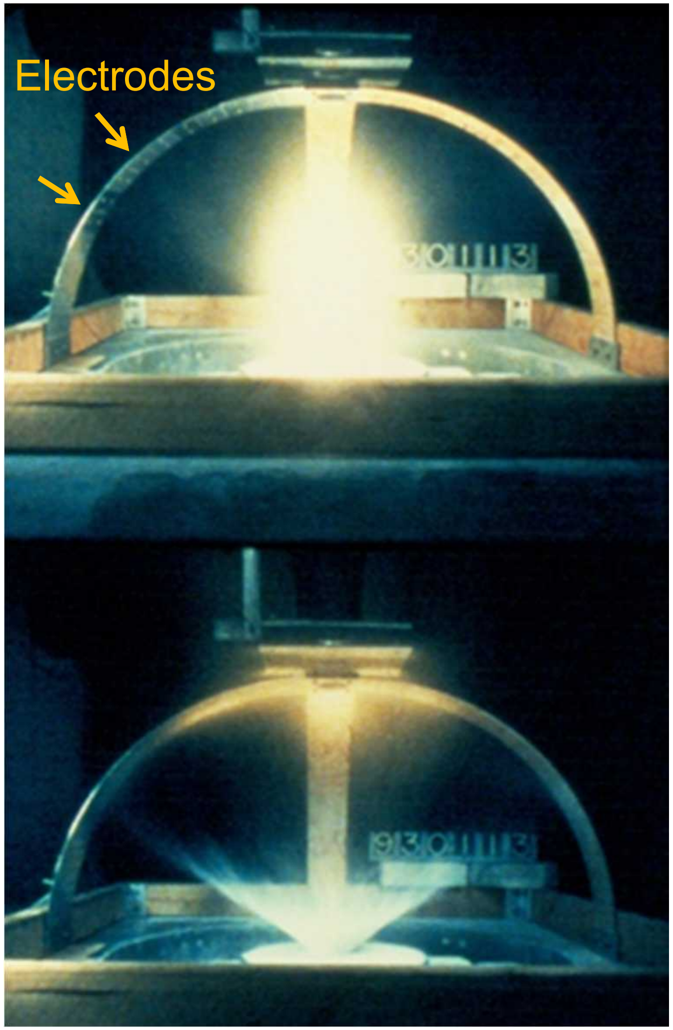
- Imbalance between ion and electron thermal currents at the contact between plasma and ejecta leads to charging of ejecta.



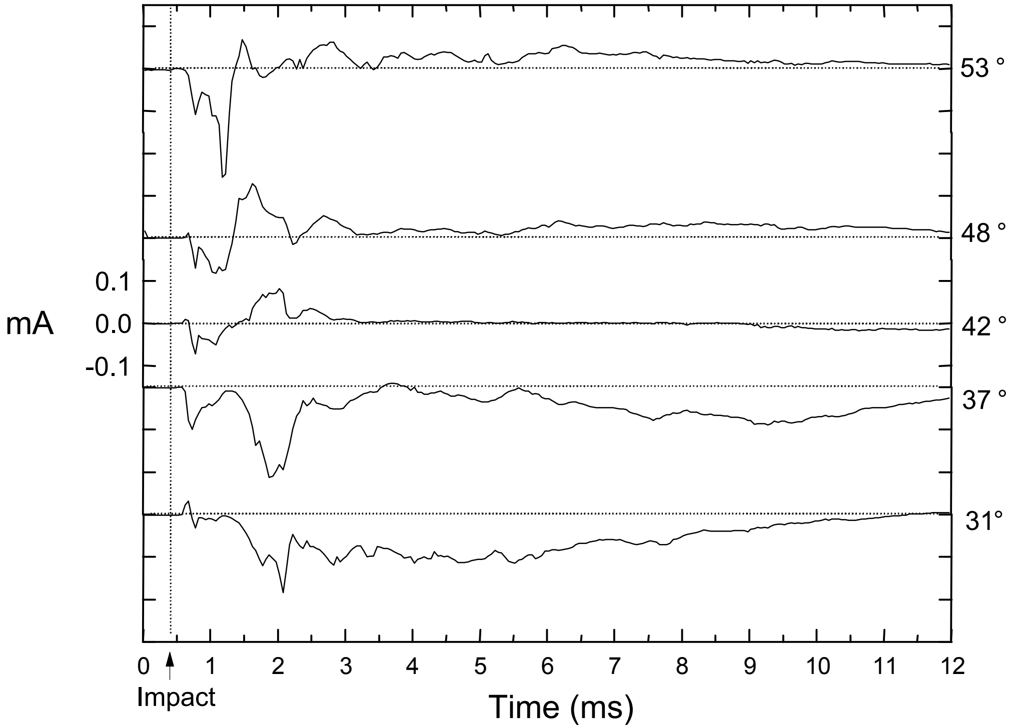
- Total amount of charge is an increasing function of impactor mass and velocity.

- Charge motion produces time-varying magnetic fields. Large impacts may produce strong fields.

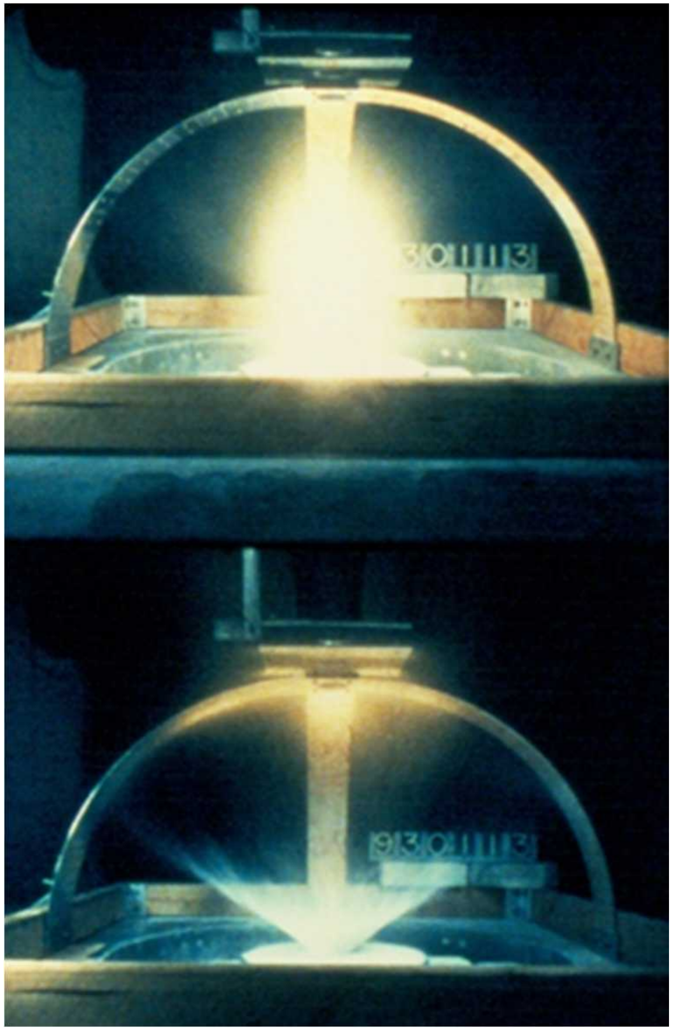
Electrostatic Experiments

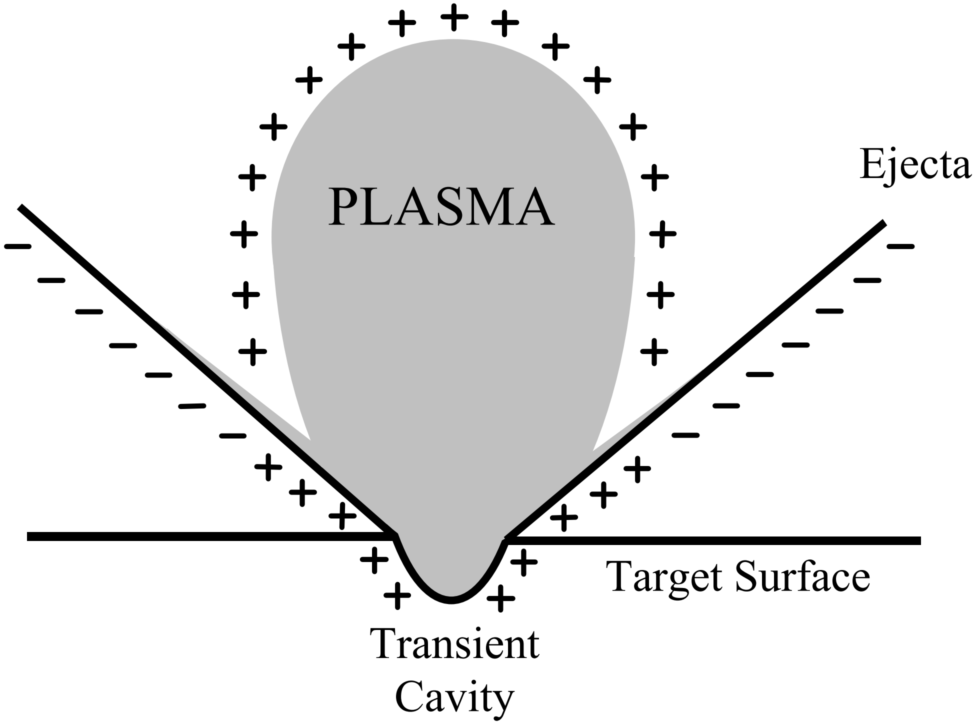


Electric current at different ejection angles

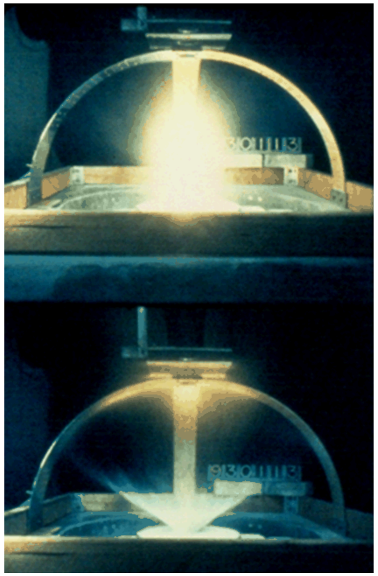


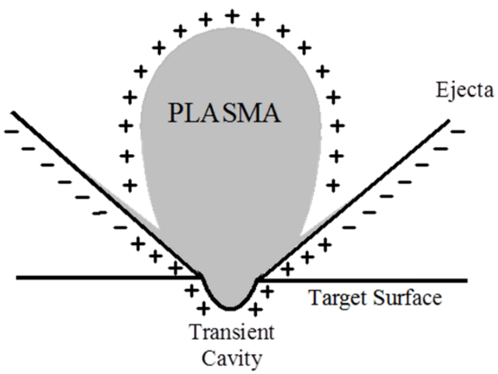
Possible charge configuration

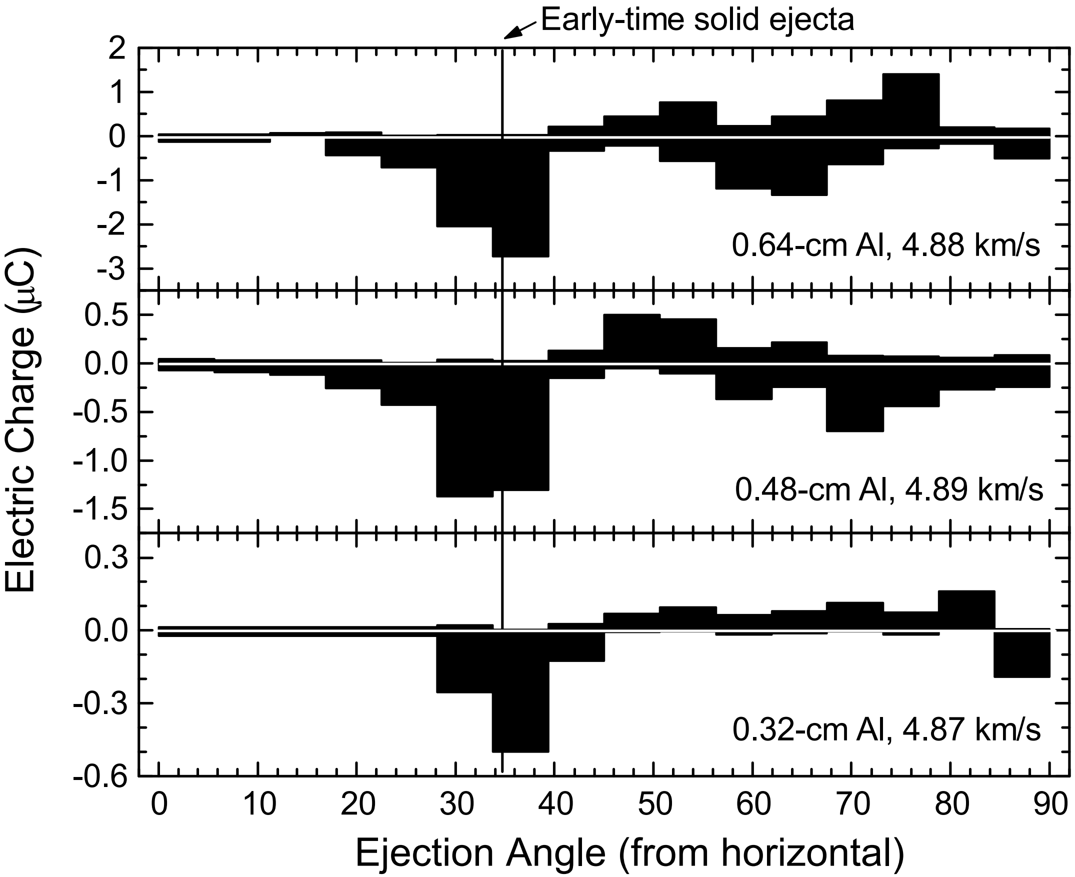




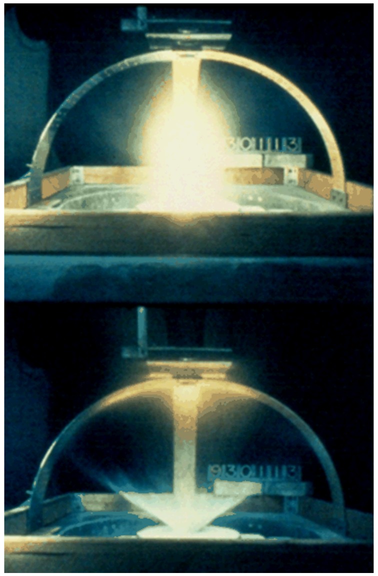
Variable Mass, Constant Impact Velocity

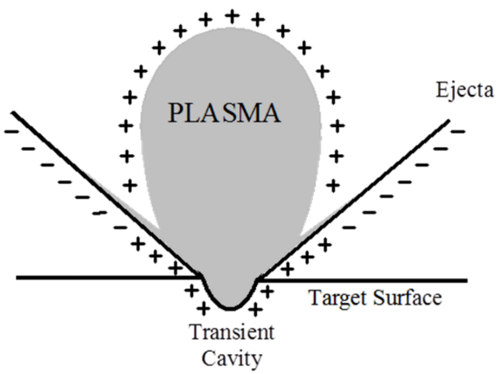


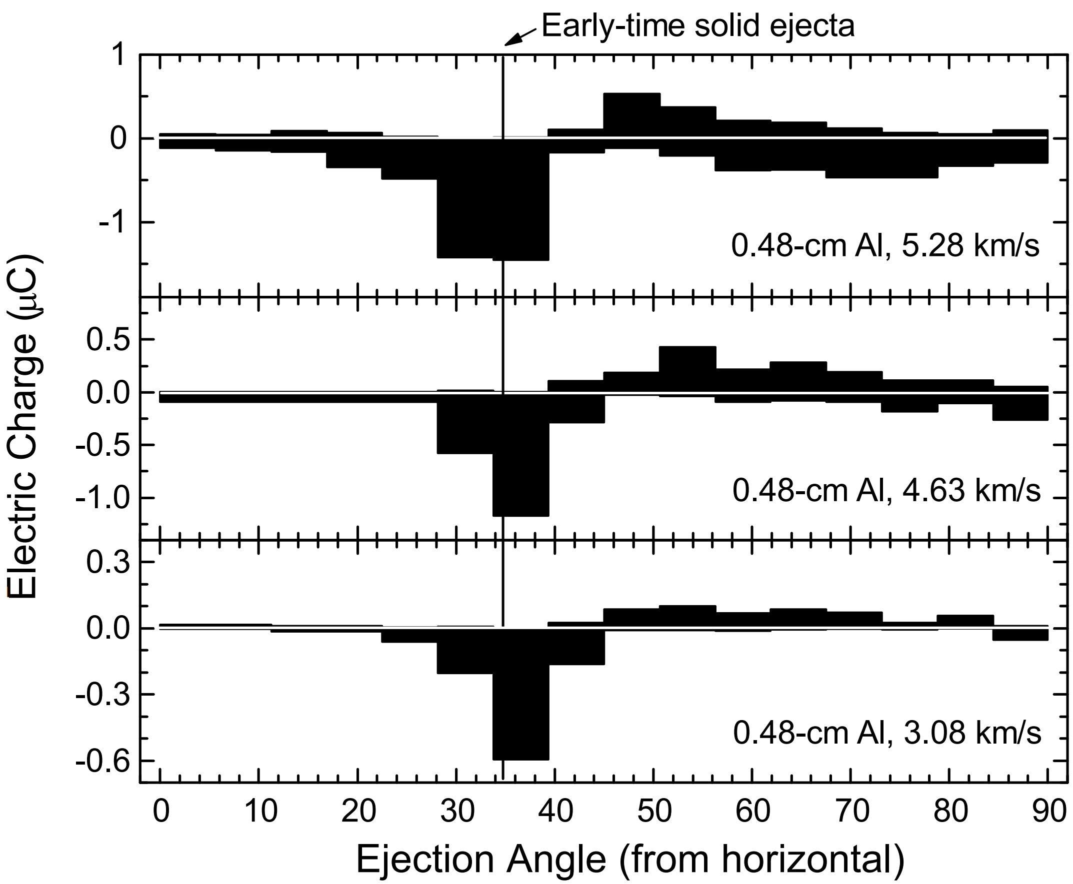




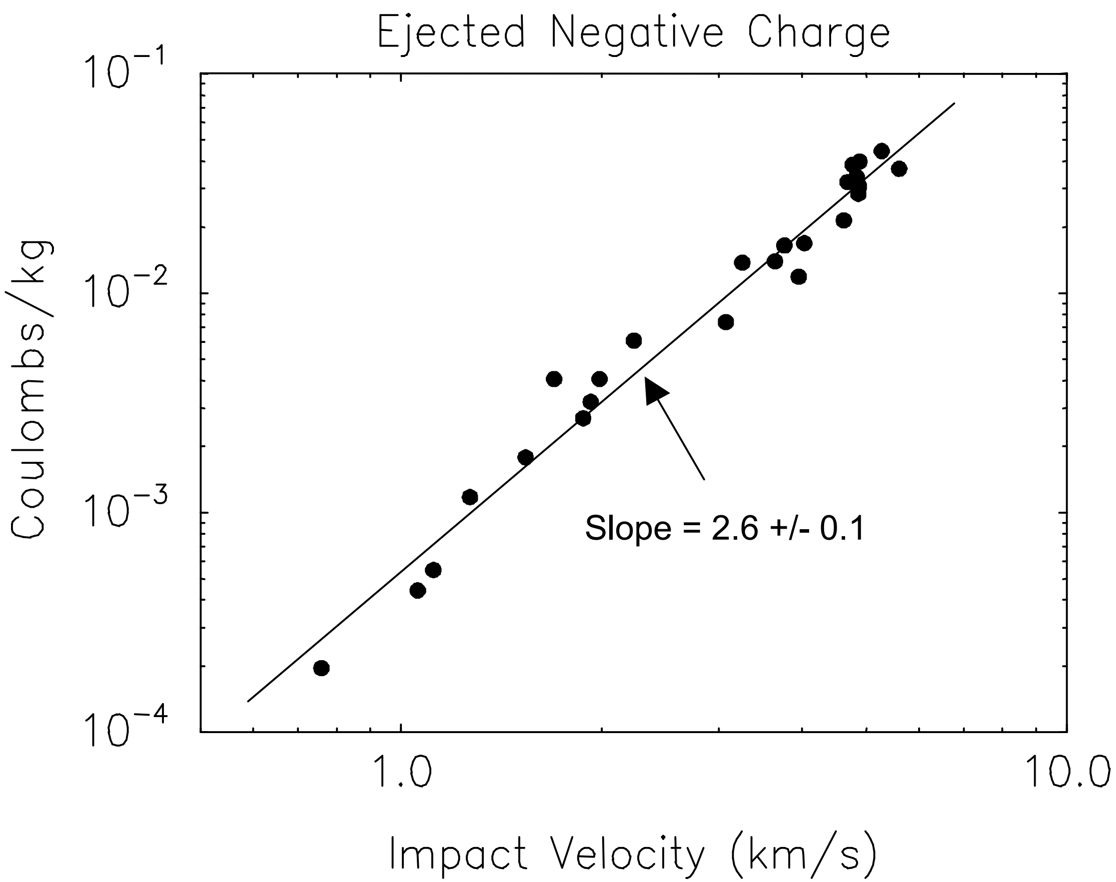
Constant Mass, Variable Impact Velocity







Dependence on Impact Velocity



Separated Charge

$$\Delta Q = 10^{-2} m \left(\frac{v}{3000} \right)^{2.6 \pm 0.1} \quad \text{C (SI units)}$$

Velocity (km/s)	*Total Charge (Q) (Coulombs)*	*Separated Charge (ΔQ) (Coulombs)*	*Degree of Separation (ΔQ/Q)*
5	0.3	4×10^{-5}	1.4×10^{-4}
20	12	1.4×10^{-3}	1.2×10^{-4}
70	380	4×10^{-2}	9.5×10^{-5}

(1 g projectile)

Assume an expanding spherical charge distribution: currents and fields

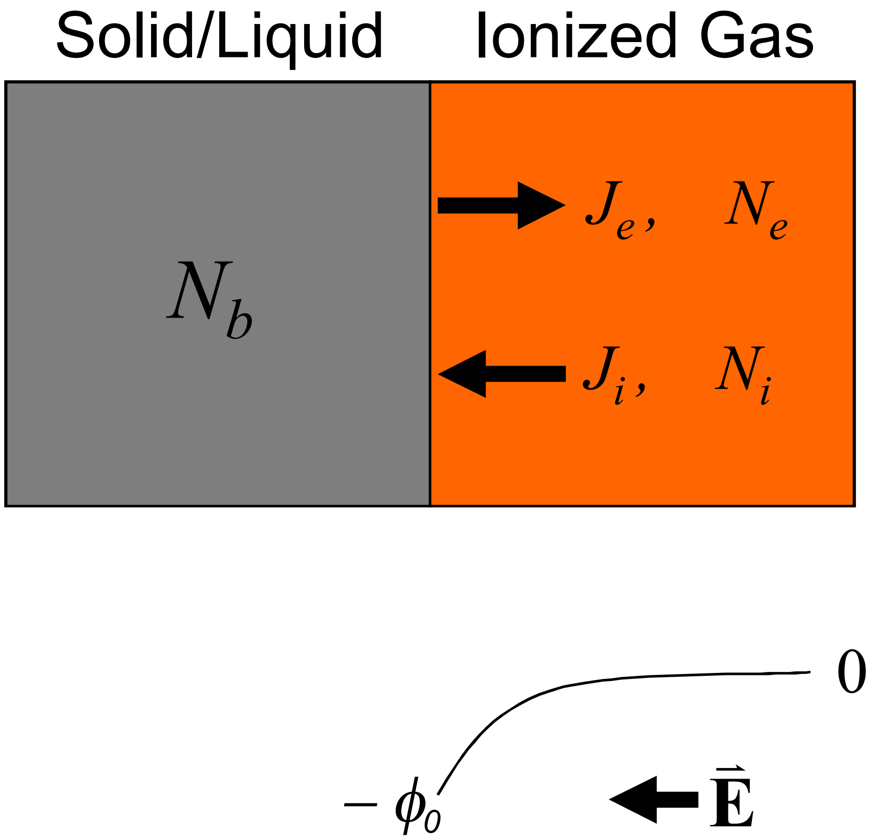
$$I = 5\times 10^{-13}\,\frac{mv^{3.6\pm 0.1}}{x}\ \text{Amps}$$

$$E = 0.24\,\frac{mv^{2.6\pm 0.1}}{x^2}\ \text{Volts/m}$$

$$B = 9\times 10^{-20}\,\frac{mv^{3.6\pm 0.1}}{x^2}\ \text{Tesla}$$

	τ (sec.)	*E (Volts/m)*	*I (Amps)*	*B (Tesla)*
1) Laboratory ($2\text{x}10^{-4}$ kg, 5 km/s)	$2\text{x}10^{-3}$	$8\text{x}10^{5}$	$4\text{x}10^{-3}$	10^{-9}
2) Cometary Meteoroid (10^{-7} kg, 70 km/s)	$3\text{x}10^{-4}$	10^{5}	0.02	10^{-8}
3) Small Meteoroid (1 kg, 15 km/s)	$4\text{x}10^{-3}$	$2\text{x}10^{9}$	180	10^{-5}
4) 1 km Asteroid (10^{12} kg, 20 km/s)	100	$4\text{x}10^{12}$	$2\text{x}10^{10}$	0.03

Simple Model of Charge Separation (based on electrostatic probe theory)



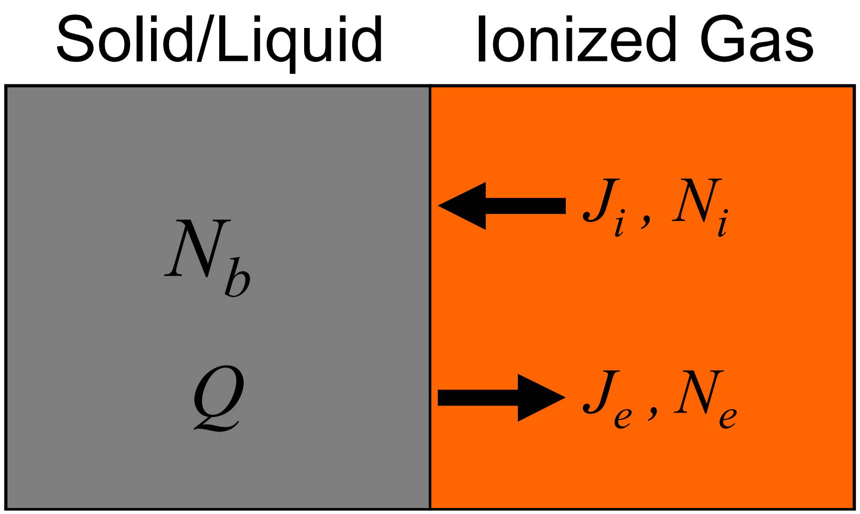
N_b becomes more *negative* as electrons attach to condensed phases

$$J_e = 0 \text{ when } N_b \leq Q_e$$

N_b becomes more *positive* as ions collide with condensed phases and recombine with bound electrons

$$J_i = 0 \text{ when } N_b \geq 0$$

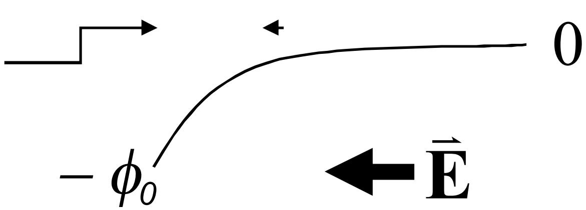
Simple Model of Charge Separation (based on electrostatic probe theory)



$$J_i = \frac{N_i}{4}\left(\frac{kT}{\pi m_i}\right)^{1/2}$$

$$J_e = \frac{N_e}{4}\left(\frac{kT}{\pi m_e}\right)^{1/2} \exp\left(-\frac{e\phi_0}{kT}\right)$$

$$\lambda_D = \sqrt{\frac{\varepsilon_0 kT}{N_e e^2}}$$



$$\phi_0 = \frac{Q}{\sqrt{2}A}\frac{\lambda_D}{\varepsilon_0}$$

Simple Model of Charge Separation (equilibrium charge)

Equilibrium occurs when $J_i = J_e$:

$$\phi_0 = \phi_e = \frac{kT}{e}\ln\left(\frac{m_i}{m_e}\right)^{1/2}$$

at equilibrium potential, ϕ_e

Equilibrium Charge (Q_e):

$$Q_e = \frac{\phi_e\sqrt{2}}{\varepsilon_0\lambda_D}A$$

where A is surface area of ejecta exposed to plasma

Adding the model to CTH

- Track gas phases and condensed phases separately using different CTH material IDs
  - Transition determined by vaporization temperature (T_v)
- Ion density (N_i) always constrained by Saha equation:

$$N_i = \left(N_k \frac{Z_i}{Z} \right)^{1/2} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/4} e^{-E_i/2kT}$$

N_k = neutral number density ($N_0 \cdot m$)
E_i = ionization energy
$Z_i/Z \sim$o(1)

- Explicitly integrate J_i and J_e to exchange charge between plasma and condensed-phase surfaces
- Limit the integration to the equilibrium surface charge (Q_e) if currents would otherwise drive surface charge past Q_e

Adding the model to CTH (cont.)

Surface area (A) of condensed phases:

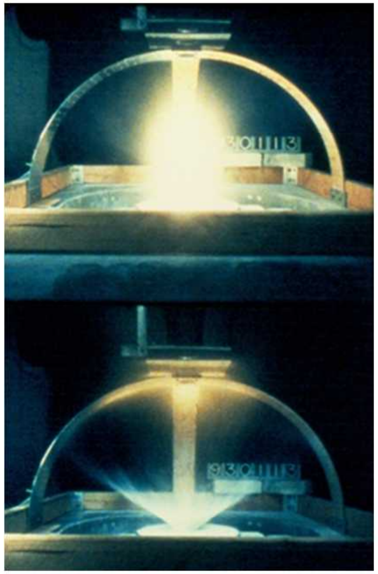
$$A = \left[\frac{M \min\left(4\pi L_p^2, A_{cell}\right)}{\rho_{ref} \min\left(\frac{4}{3}\pi L_p^3, V_{cell}\right)} \right]$$

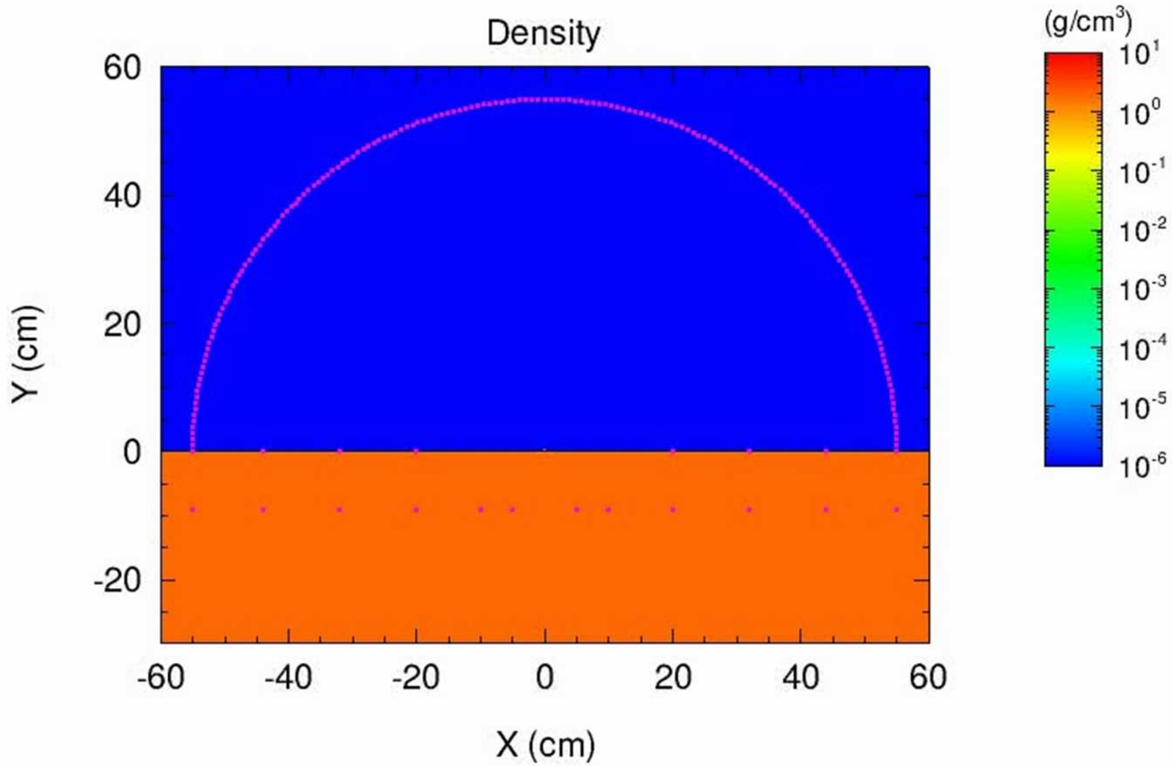
L_p is particle size from user input

Parameters for the CTH Electrostatics Model:

	Aluminum	Air	Calcite
N_0 (g^{-1})	2.23x10^{22}	4x10^{20}	6x10^{21}
E_i (eV)	5.99	9.26	6.11
Z_i / Z	0.17	1	1.74
m_i (amu)	26.98	30	40
T_v (eV)	0.24	0	0.09
L_p (cm)	0.01	N/A	0.05

CTH calculations using the charge separation model





Time = 0.00e+00 s.

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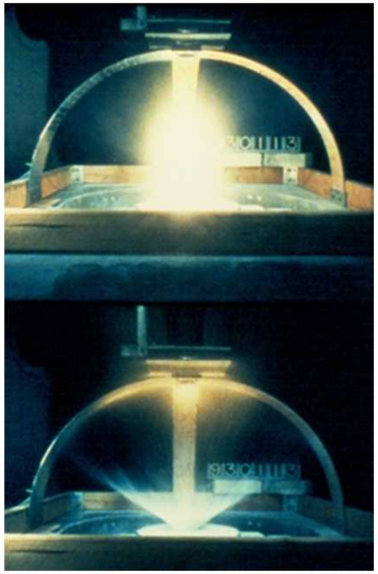
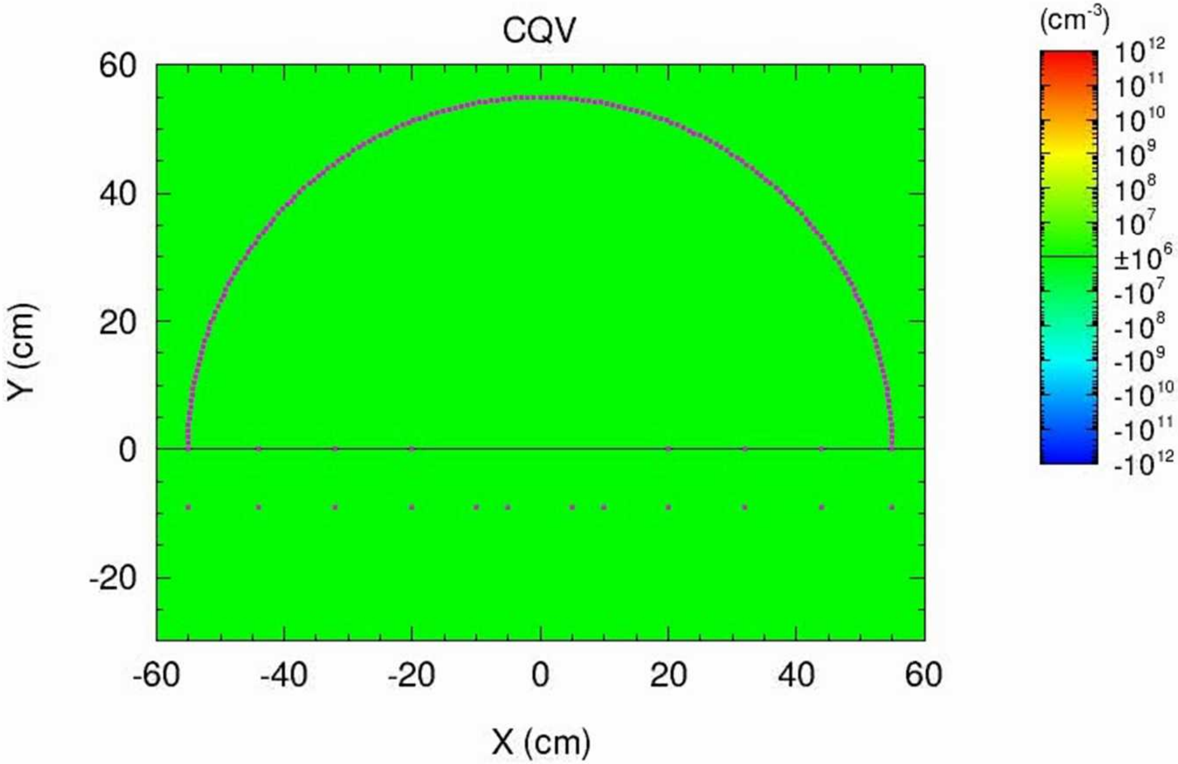
CTH calculations using the charge separation model





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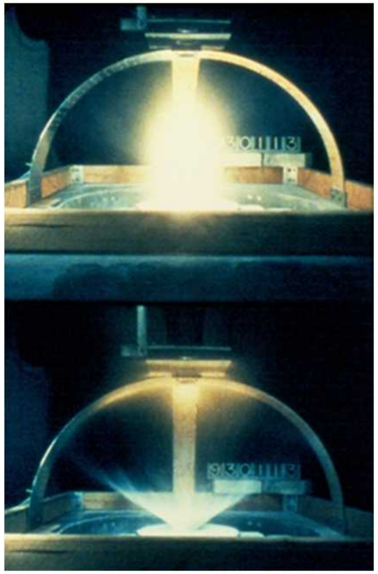
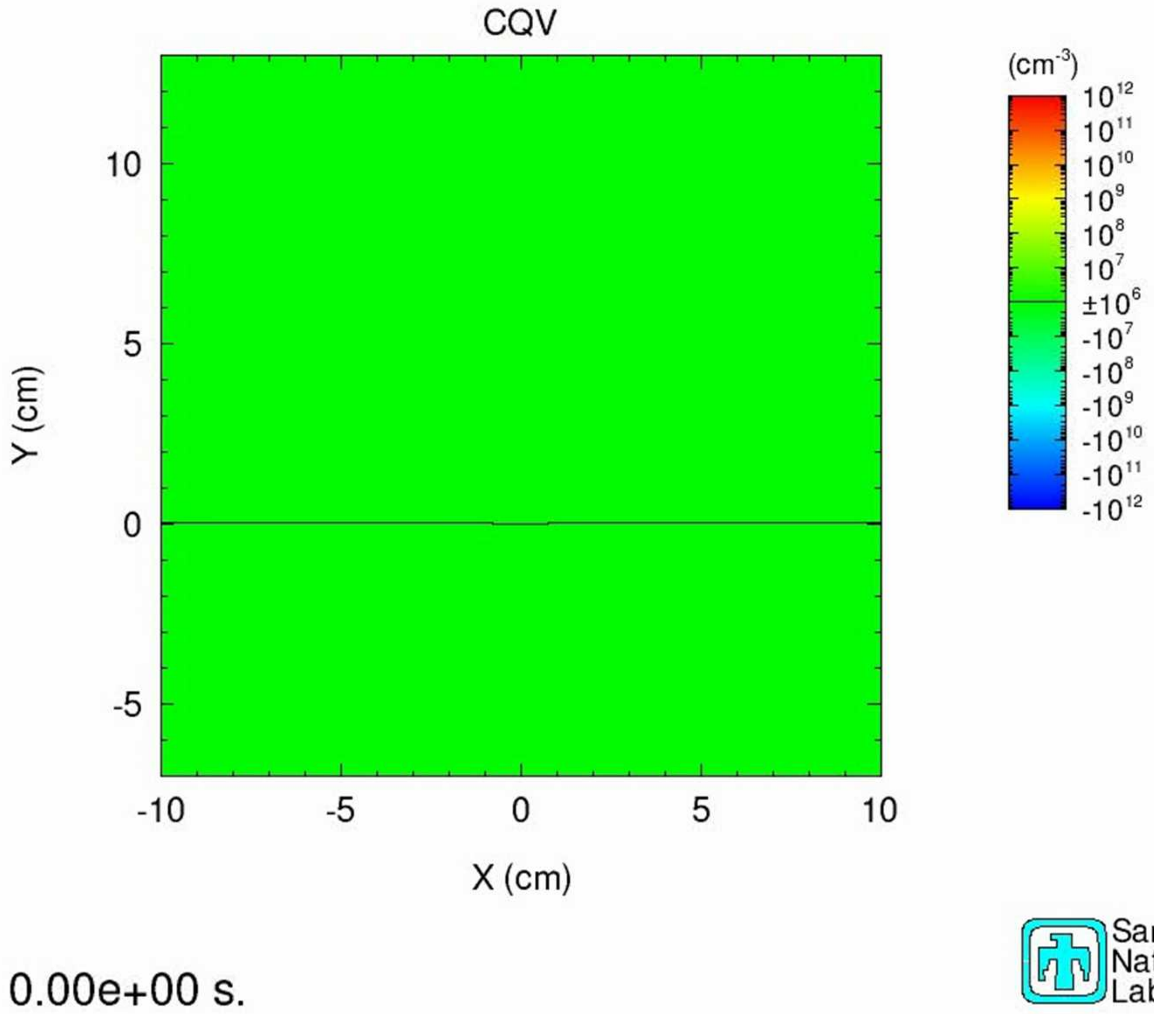
CTH calculations using the charge separation model





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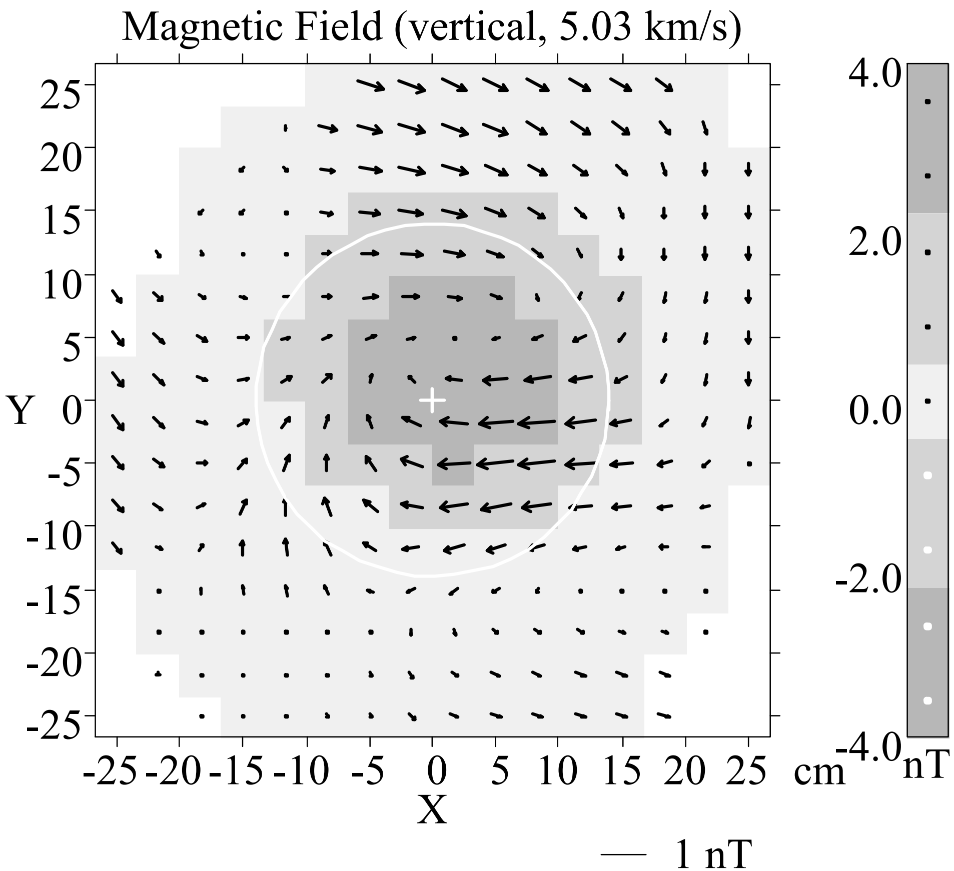
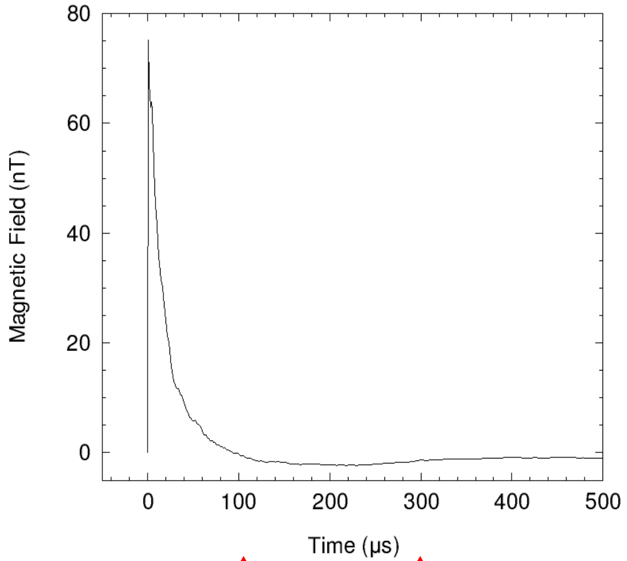
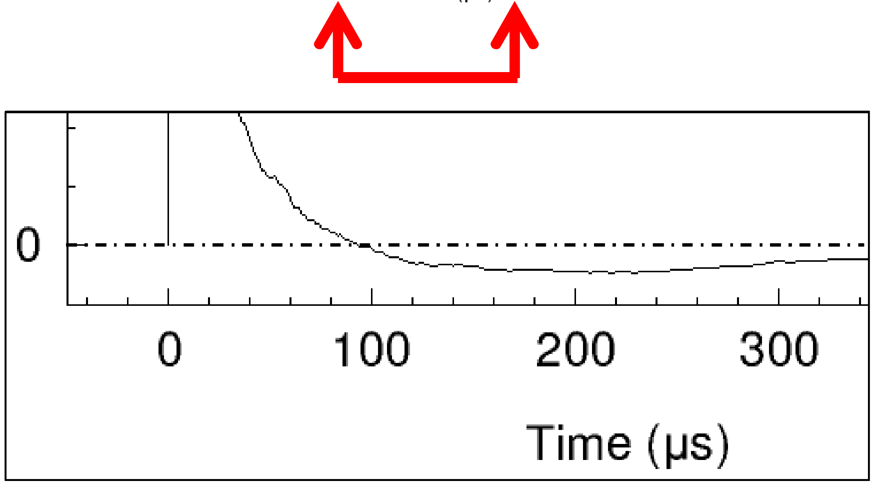
Calculated Magnetic Field vs. Measured Field

Experiment (100-300 μs)

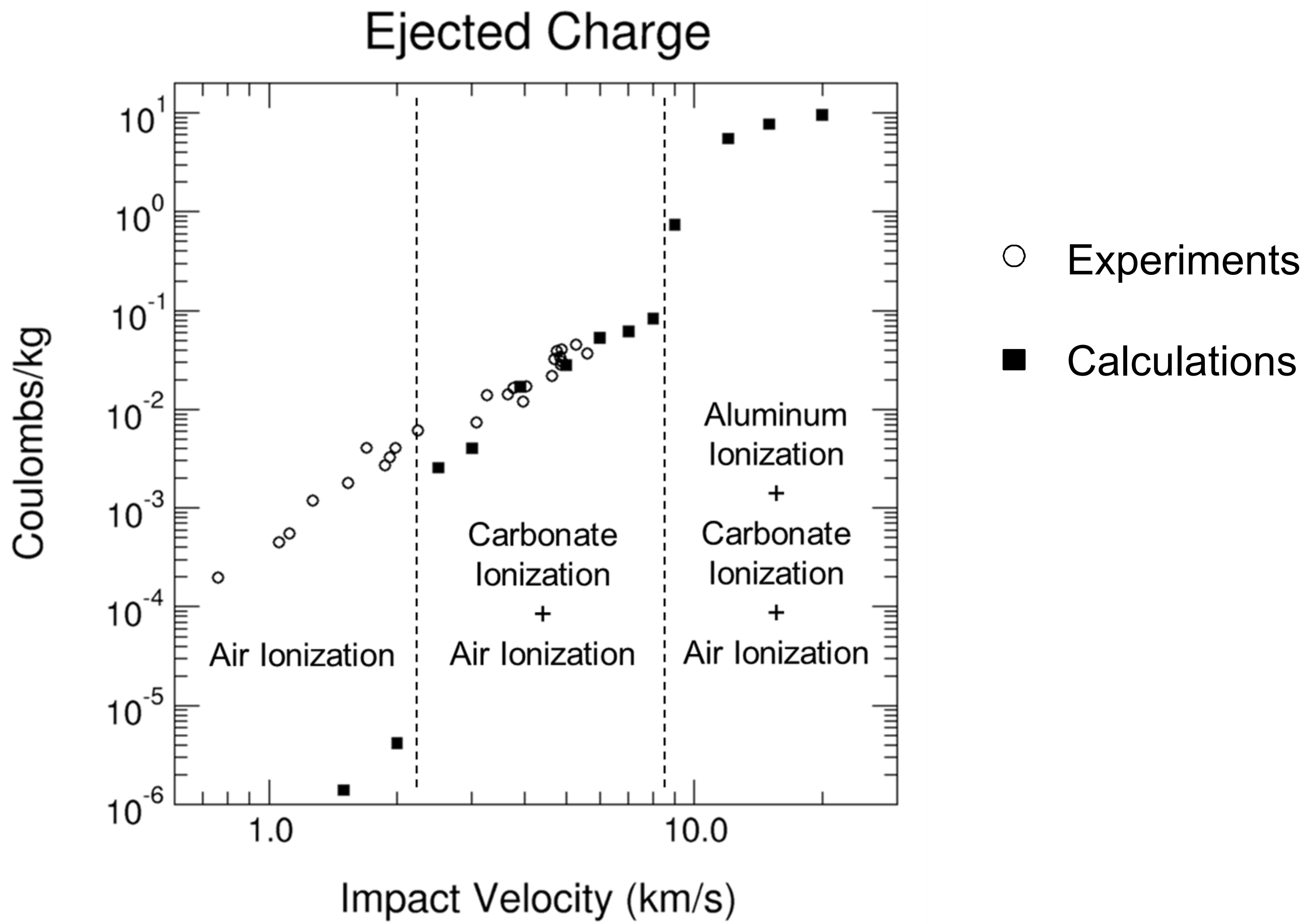


Calculation

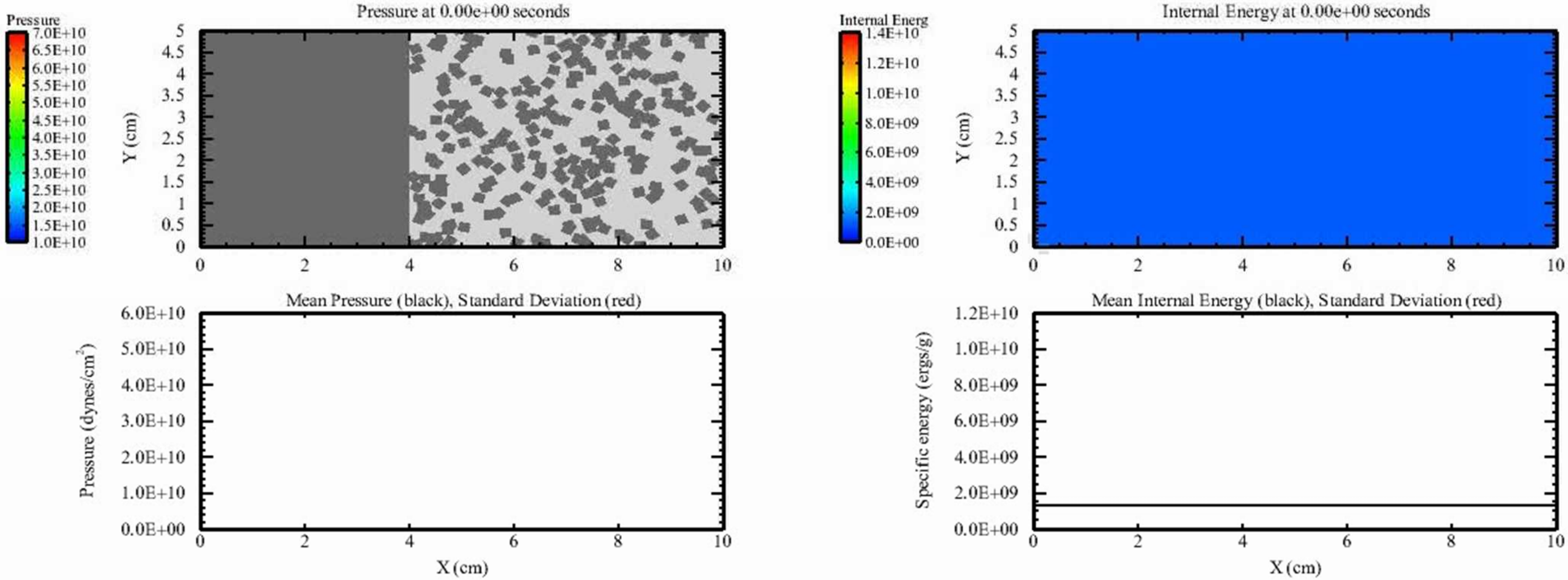




Calculated Charge vs. Experimental Measurements



Pore Collapse Role in Ionization?



Saha Equation: $$N_i = \left(N_k \frac{Z_i}{Z} \right)^{1/2} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/4} e^{-E_i/2kT}$$

Conclusions & Future Work

- Production of charged debris will occur in impacts wherever plasma and dust co-mingle.
- Magnitude of charge, currents and fields increase with impactor mass and velocity

  $Q \propto m^{0.67\text{-}1.0} v^{2.6}$

- Computer simulations show reasonable agreement with experimental data.
- Ongoing Development & Future Computational Work
  - 3-D simulations
  - Predicting remanence