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A fragmentation model approach for low velocity impact charging

Implications for dust observations with rockets and spacecraft

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Abstract

We investigate the generation of charge during collision of projectiles with sizes below 1 micron and metal surfaces at speeds ~0.1 to 10 kms^{-1}. This corresponds to speeds above the elastic limit and well below speeds where volume ionization can occur. The conditions that we consider apply to dust particles naturally occurring in space and in Earth's upper atmosphere and their direct impacts on rockets, spacecraft, and impacts of secondary ejecta. We introduce a model of capacitive contact charging in which we allow for projectile fragmentation upon impact, and show that this model describes measurements of metal-metal impacts in the laboratory and in-situ measurements of dust in the Earth's atmosphere well. We have considered the utilization of our model for different scenarios in interplanetary space and in Earth's atmosphere. From this discussion we find it likely that our work can be employed in a number of situations where impact velocities are relatively small. Furthermore, we have discussed the thermodynamics of the low velocity solution of shock wave ionization, and conclude that the impurity charging effect utilized in the much used model of Drapatz and Michel (1974) does not sufficiently describe charge generation at impact speeds below a few kilometers per second. Consequently, impact charging at low speeds cannot be described with a Saha-solution.

Related publication: *A Comparison of Contact Charging and Impact Ionization in Low Velocity Impacts: Implications for Dust Detection in Space.* Subm. ANGEO (2020)

Overview

Status

- Impacts of projectiles – dust, micrometeorites – can generate charge by plasma production.

- Charge production semi-empirically quantified by:

$$Q \sim m^{\alpha} v^{\beta}$$

Where m and v is projectile mass and velocity. Typical values: α ~ 2/3 – 1 and β ~ 3 – 6

- **Mechanism**: Shock waves in both projectile and target produce ionization which can be described by a Saha-equation †

- The model above describes the velocity regime from a few km/s to some tens km/s. For lower velocity range: impurity ionization important.

This work

- We suggest that shock wave **impact ionization cannot sufficiently explain** laboratory and rocket measurements of dust impact charging at speeds below a few km/s.

- At velocities well below the sublimation threshold, capacitive (contact) charging can become dominant.

- We propose a model where incoming conducting projectiles fragment, and the individual fragments have a capacitive coupling with the target surface.

- Contact charging important at impact speeds up to some km/s.

- Obtain scaling: $Q \propto r_p^3 \ln\left(\frac{r_p v_p^{4/15}}{r_{\min}}\right)$

Where $\mathbf{r_p}$, $\mathbf{v_p}$ is projectile radius and speed.

$\mathbf{r_{min}}$ is the minimum fragment size – typically below 1 nm.

† Drapatz and Michel (1974) *Zeitschrift für Naturforschung A*, *29*(6), 870-879

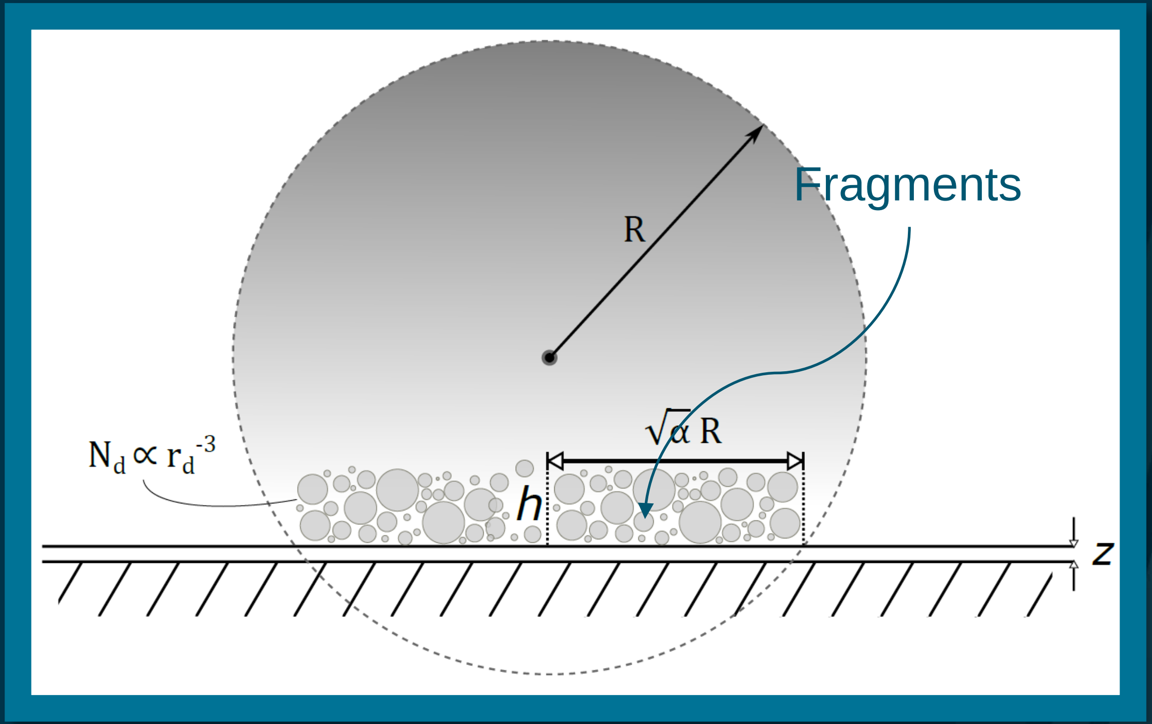
Capacitive Charging Geometry

- We utilize Hertzian deformation theory, assuming plastic projectiles.
- Charge production proportional to area of fragments $A = \alpha \pi r^2$, where

$$\alpha = \left(\frac{5}{4}\pi^2 \rho_p v_p \left[k_t + k_p\right]\right)^{\frac{2}{5}}$$

- The difference in work function between fragments and target sets up a potential V in which electrons can move from one surface to another [Wang & John 1988, John 1980]
- It can then be shown that: $Q \sim CV\left(1 - e^{-\frac{t}{\tau}}\right) \sim r_p^2 v_p V \left(\frac{\rho}{Y}\right)^{1/2}$

Where ρ is mass density, Y is yield stress, C is capacitance, $e^{-t/\tau}$ is the transient relaxation factor, v_p and r_p velocity and radius of projectiles (fragments). We focus on the (semi-) conducting case $\tau \gg t$



*Contact geometry for the charging model of capacitive contact charging. The d subscript denotes dust here. We assume that the resulting **size distribution of fragments** is proportional to r $^{-3}$.*

Results for Fe – Ag collisions

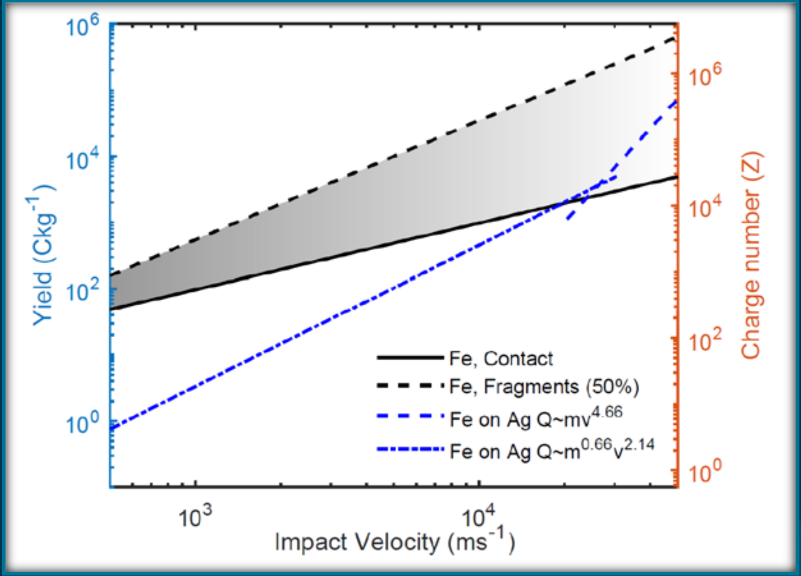
- At default model parameters, our model predicts a higher yield than laboratory experiments† (see figures).

- Tuning the parameters give a good fit, with a similar dependency on radius (Yield ∝ cross-section).

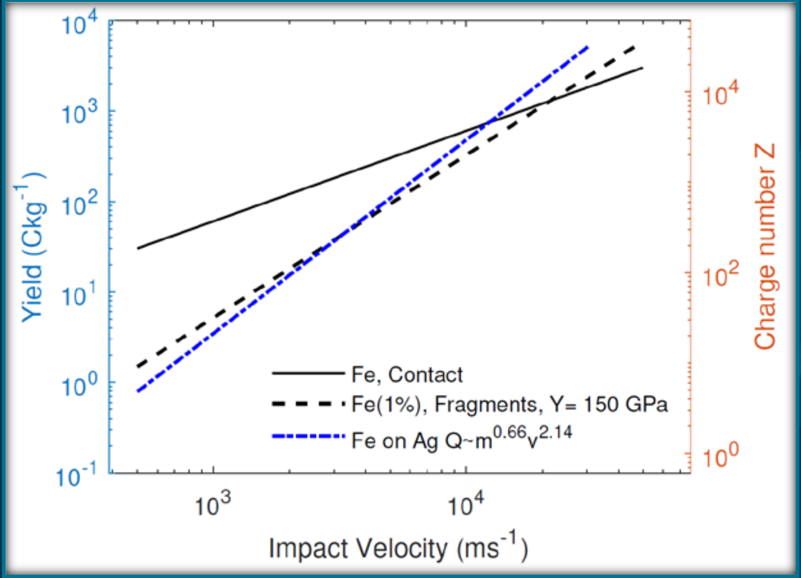
- Moderate dependency on parameterization of fragment size distribution – e.g. minimum fragment size.

- **Note**: Our model is probably not valid at speeds above a few km/s, as sublimation and evaporation at impact will become dominant

Our default model for iron projectiles (r_p = 30 nm) on a silver target with (black dashed) and without (black solid) a fragmentation model. Semi-empirical laws obtained in the laboratory by Mocker et al. (2013). Here Y = 50 GPa, and fragment size span [0.5, 3] nm.



Best fit for iron projectiles (r_p = 30 nm) on a silver. Here Y = 150 GPa, and fragment size span [0.7, 3] nm. Charge yield factor reduced to 1%.

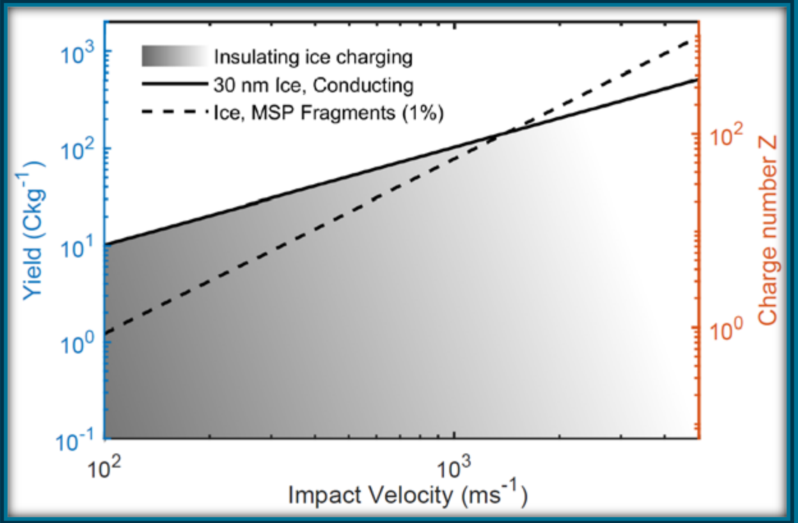


† Mocker et al. (2013) *Planetary and Space Science*, *89*, 47-57

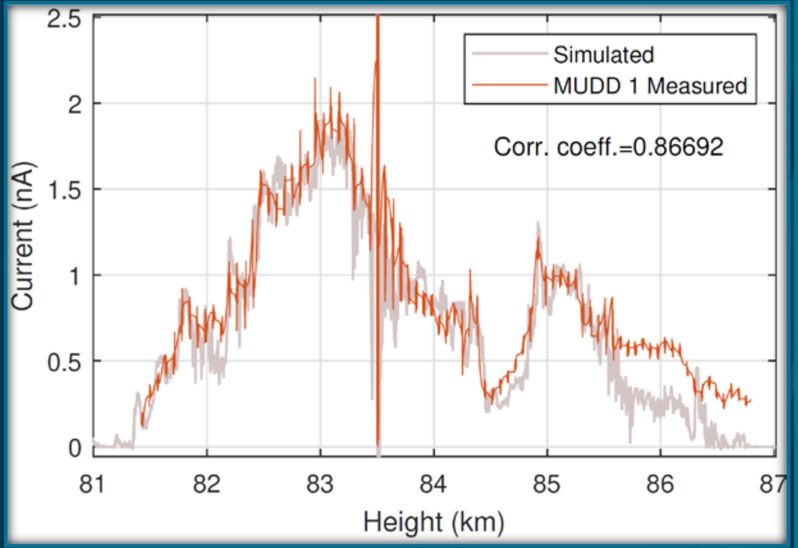
Results for Ice – Stainless Steel

- Use model parameters suitable for aerosols in the Earth's mesosphere: Ice particles with embedded meteoric smoke particles.
- Ice fragments will not contribute significantly to the charge production.
- MSPs follow similar size distribution as fragments in the Fe-Ag case.
- **Very good agreement** with rocket measurements of mesospheric dust – MAXIDUSTY payloads; bottom figure.

Charge yield of 30 nm ice particles with MSP impurities impacting on stainless steel. The shaded area shows possible yields for the case of a mixture of insulating and conducting particles



Measurements from the impact Faraday cup MUDD on the MXD-1 rocket payload (red) and a **best fit** from simulation of contact charging (grey) using our model. V = 0.5 eV was found to be the best fit for fragments of density 3 gcm^{-3} and yield pressure 50 MPa. The minimum fragment size threshold was set to 0.3 nm



Model parameters:
V = 0.5 eV
Density 3 gcm^{-3}
Yield pressure 50 MPa.
Minimum fragment size threshold 0.3 nm

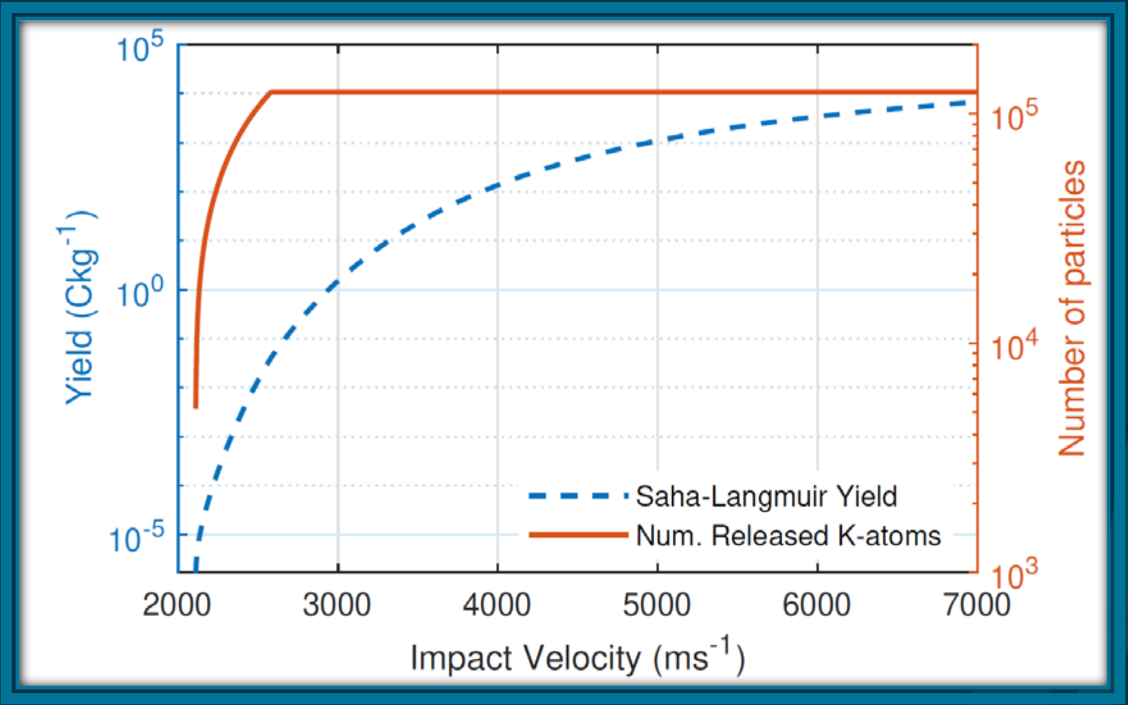
A note on the low velocity solution of Drapatz and Michel

- We find that the original work on shock wave ionization probably overestimate the charge production at low speeds.

- This is mainly due to utilizing unrealistic cooling rates and solidification times for submicron fragments or droplets.

- We find, with updated parameters, that the limit for impurity ionization production is around 1 km/s for an iron grain.

- Using the Saha-Langmuir eq. (Saha-eq. with electrons bound in conducting surface) we can estimate the yield due to impurities.



Impurity charging (1% Potassium) using the Saha-Langmuir equation (blue, dashed) and our fragmentation parameterization. The solid red line show the number of released K-atoms as a function of velocity, and therefore constitutes a theoretical upper bound on the charge number (for singly charged ions). The resulting yield is vanishing at impact speedslower than ~2 km/s.

Implications for dust detection in space

- **Dust on spacecraft**. For certain orbits, direct impacts of low velocities may happen. Secondary ejecta (of e.g. beta-meteoroids) might be candidates for our model. Relevant for PSP, ESO.

- **Space debris**. Dust have been detected on Earth orbiting satellites; e.g. MMS and Cluster. These have significantly lower impact speeds than interplanetary dust.

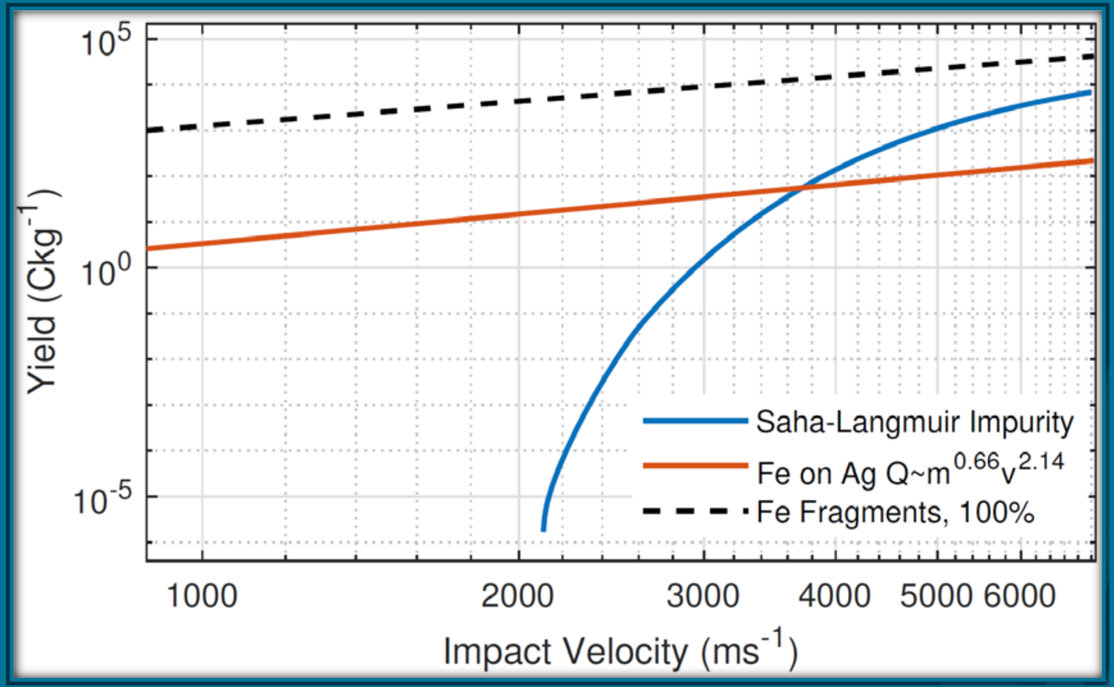
- **Dust in the Earth’s upper atmosphere**. Rockets readily observe dust at speeds ~1 km/s. Our model can be utilized in studies investigating e.g. noctilucent clouds and meteoric smoke particles.

ESA | NASA
solar orbiter

Parker Solar Probe

Conclusion

- We find that our contact charging and fragmentation model is consistent with laboratory measurements of Fe-on-Ag collisions as well as rocket measurements of icy dust particles on stainless steel. Our method can be utilized with a large range of projectile dust types, where the intrinsic properties of the grains are known.
- We moreover find that the currently accepted theory for impact charging at the speeds of interest here, namely the shock wave ionization theory of Drapatz and Michel (1974), is insufficient in explaining laboratory observations of charge generation in metal-on-metal impacts. Consequently, we suggest that at low speeds, there must be a significant contribution to the produced charge by contact charging.



Comparison of specific yields from our contact charging model (dashed) to the Saha-Langmuir solution from Drapatz and Michel (1974) (solid blue) and the semi-emprical law obtained by Mocker et al. (2013) (solid red).

Acknowledgements

This work was supported by the Research Council of Norway through grant number 262941. The rocket campaign and the construction of the rocket instrumentation was supported by grants from the Norwegian Space Centre (VIT.04.14.7, VIT.02.14.1, VIT.03.15.7, VIT.03.16.7) and the Research Council of Norway, grant 240065. J.V. and L.N. were supported by the Czech Science Foundation under Project 20-13616Y. We thank the International Space Science Institute in Bern (ISSI Bern) for their support through funding of collaborative meetings on "Physics on Dust Impacts".