Laboratory Simulations of Aluminum Micrometeoroids

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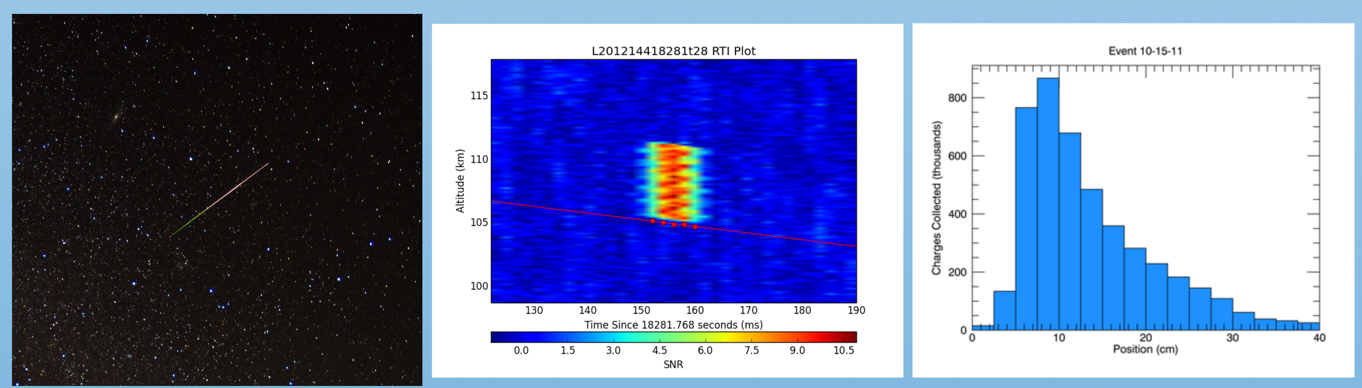
Abstract: We simulated micrometeoroids entering planetary atmospheres in the lab to determine the ionization coefficient of aluminum at a range of velocities. These experiments utilized a 3 MV hypervelocity dust accelerator to shoot submicron-size dust particles into an air chamber. When dust particles entered the chamber, they produced charges that were collected inside of the air chamber. Photomultiplier tubes (PMT's) also observed the light produced by the particles as they ablated. Aluminum dust particles were shot into the air chamber at speeds between 10 and 70 km/s. By adjusting the pressure such that the dust particles completely ablated, the ionization coefficient β was measured as a function of velocity. The β values are fit to a curve described by Jones [1]. The ionization coefficient β is the probability that an ablated atom will ionize, and it is important for the determination of meteor mass from radar observations of meteors. The PMT's observe photon production by the dust particle as it travels through the chamber, allowing the particle itself to be tracked as it travels through the chamber. A new pickup tube detector is also under development to observe the slowdown of the dust particles as they travel through the chamber.

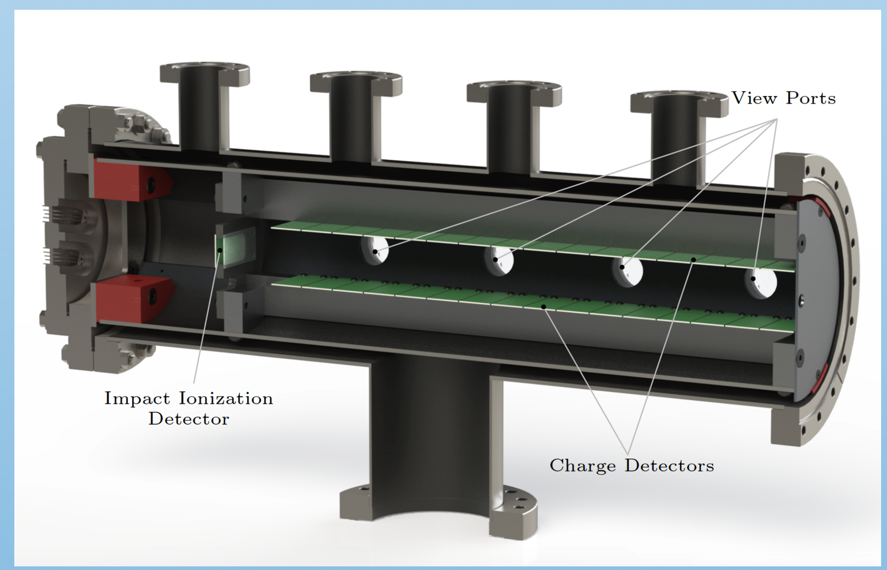


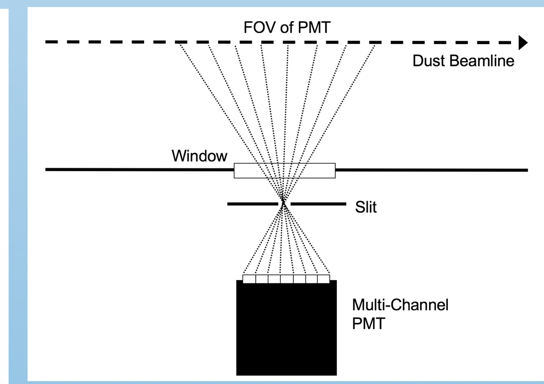
Left: A meteor observed in optical light [2]. Middle: A radar observation of a meteor. HPLA radars detect electrons that form a head echo around the meteor. Right: A simulated meteor observed in the lab. We collect electrons (or ions) produced by a simulated meteor.

Introduction: The inner Solar System is full of dust, which the Earth collides with during its orbit around the Sun. This cosmic dust enters Earth's atmosphere as meteors. The distribution of these particles peaks at 1-10 μg in mass [3], and most fully ablate between 80-120 km in Earth's mesosphere. High-power large aperture (HPLA) radars can detect the head echoes that form around these small particles while they ablate. Since these radar systems are sensitive to small particles which provide the bulk of meteoric input, they are the best tool that we have to constrain the total cosmic dust input to Earth. Current estimates of the mass input range from 4 – 240 metric tons per day [3]. Better constraining the input mass will have implications for models of dust in the Solar System and their source bodies: asteroids and comets. It also has implications for planetary atmospheres, as meteors deposit metals such as Fe, Na, Ca, and K into the upper atmosphere when they ablate.

Image of a comet [4]. Meteor observations help to constrain the properties of both interplanetary dust and its source bodies, including comets and asteroids.

Experimental Setup: When meteoroids enter planetary atmospheres, they heat up and ablate. The ablated atoms are ionized through collisions with molecules in the atmosphere, leading to the formation of electron-ion pairs. In this experiment, we shot aluminum dust particles into an air chamber at velocities between 10 and 70 km/s. The air chamber is filled with gas held at a constant pressure, typically around 0.1 Torr. Hundreds of aluminum particles entered the air chamber during the experiment, and for each particle both light and charge measurements were made. The charge measurements were made using 16 biased charge collectors inside the chamber. The light measurements were made with an array of four 16-channel PMT's which viewed the inside of the chamber through view ports. A slit was placed between each PMT and the view port such that the field-of-view of each PMT channel was mapped to a 6.25 mm-long portion of the beamline.





Diagrams of the Ablation Chamber [5] and PMT Setup.

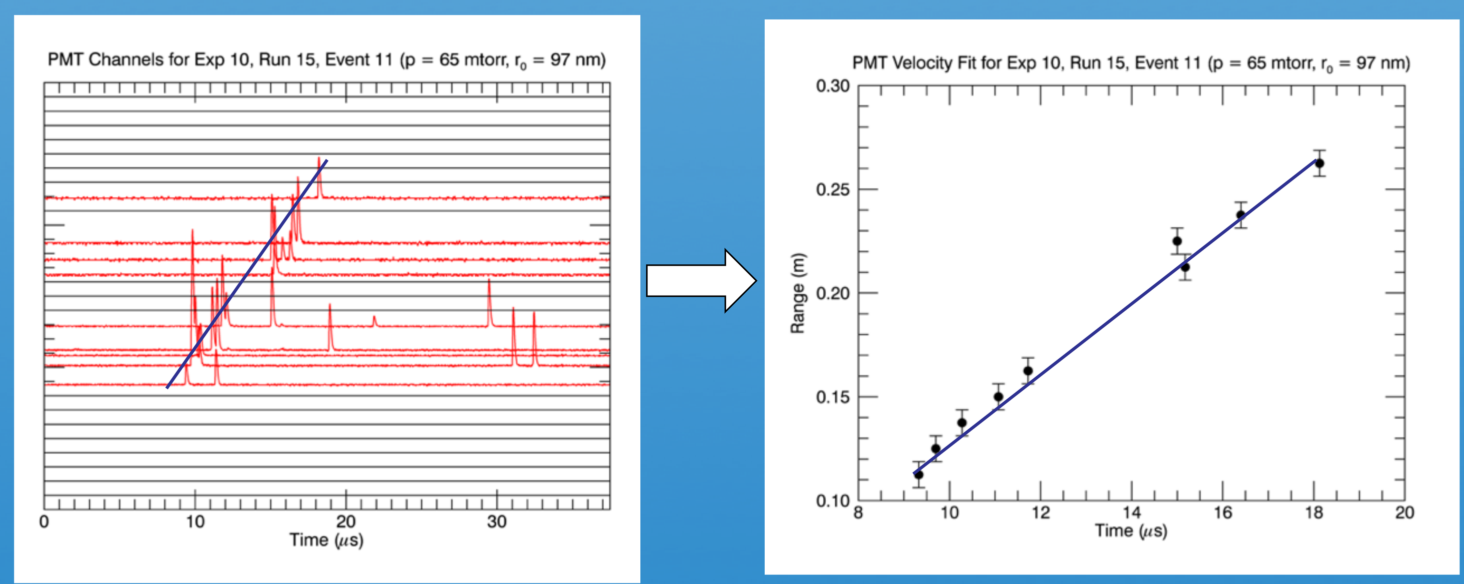
Methods: We calculated he ionization coefficient β for a particle by dividing the total number of charges collected (electrons or ions) by the number of atoms in the particle. Only dust particles that fully ablated were used in this analysis. The data was then fit to a curve described by Jones [1]:

$$\beta(v) = \beta_0(v) + (1 - \beta_0(v))\frac{(1+\mu)^2}{2v^2\mu}\int_{v_0}^{v}\beta(v')v'dv'$$

$$\beta_0(v) = \frac{c(v-v_0)^2 v^{0.8}}{1 + c(v-v_0)^2 v^{0.8}}$$

A least-squares fit was used to determine the Jones parameter c for aluminum.

We used the PMT observations to track particles as they traveled through the air chamber. The light produced by the passage of the particle produces a series of pulses on the different PMT channels which can be used to track the particle's position.



Left: The observed PMT pulses. The channels are artificially stacked from bottom (nearest the chamber entrance) to top (nearest the end of the chamber). Right: The observed time and position of the particle from the PMT observations.

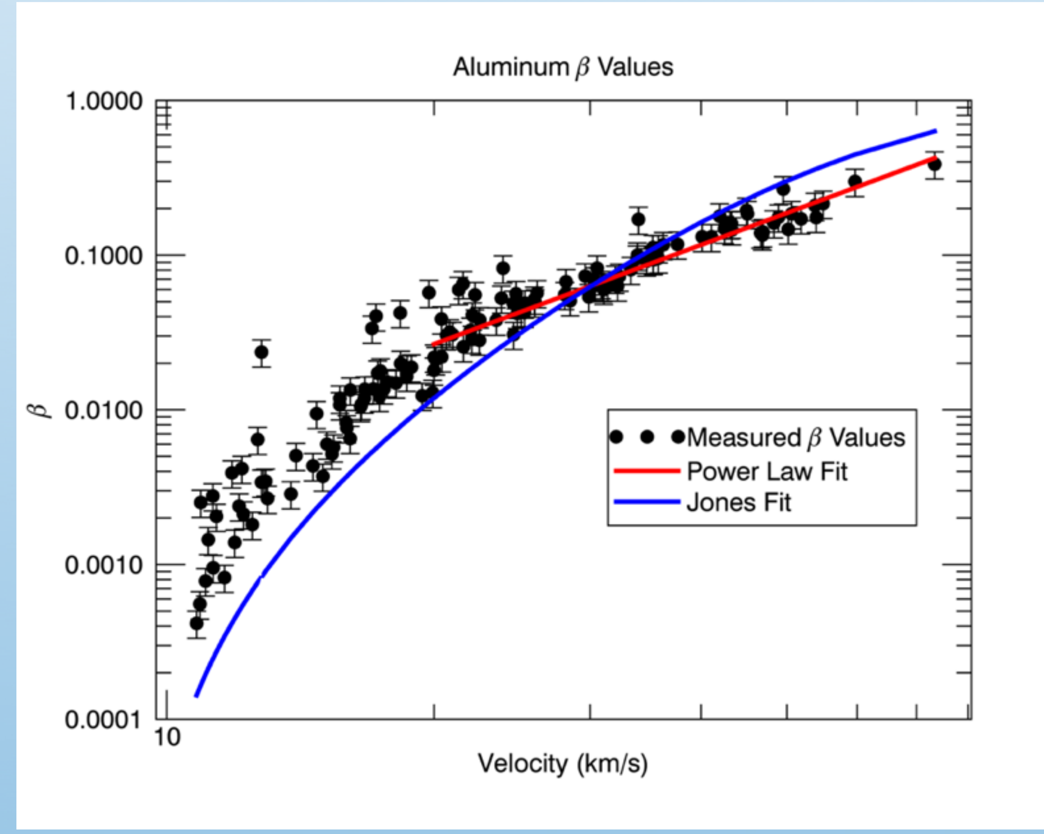
Slowdown is important to measure because deceleration of the particle will reduce the total number of charges collected. This effect will bias β measurements to be lower than they would be without slowdown, and is most pronounced at low velocities where the β curve is steepest. The effect causes our β measurements to be lower limits on the true β values.

Results: Using the data, we calculated the values of β for particles between 10.8 km/s and 73.4 km/s, shown below. We then calculated the Jones parameter for aluminum:

$$c = 6.69\times10^{-6}\ (s/km)^{2.8}$$

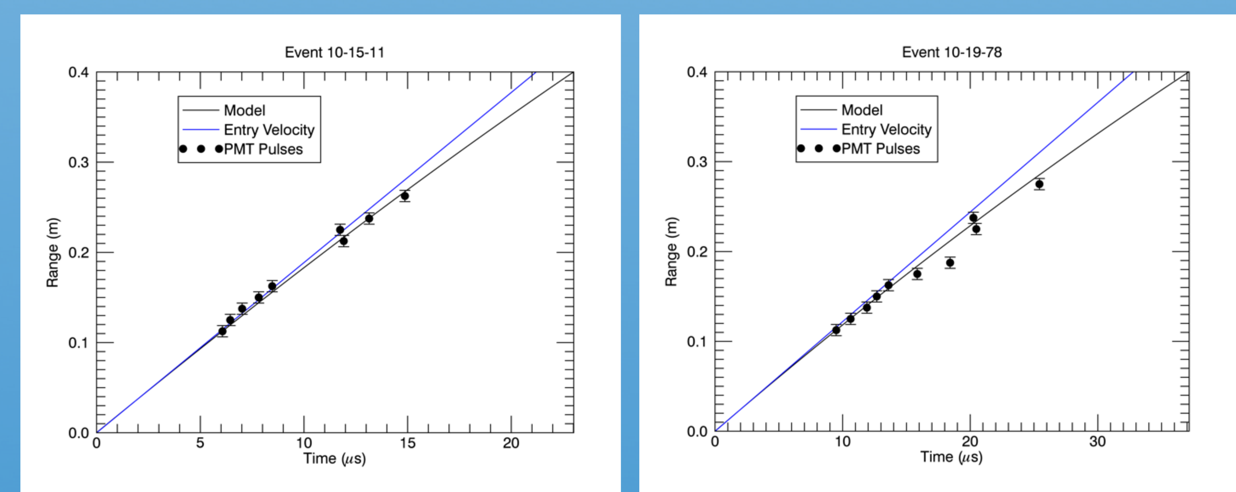
For velocities above 20 km/s, the β values follow a simple power law of the form:

$$\beta(v) = 4.49\times10^{-5}v^{2.13}$$



The Jones curve shown here illustrates the problem with using it to determine β values. The best-fit Jones curve is not a good fit to the experimental data. It tends to over-predict the value of β at high velocities and to under-predict the value of β at low velocities. Note that the low-velocity measurements are also under-predictions due to slowdown, making the Jones fit worse.

We were able to observe the slowdown of some of the particles using the PMT's. Two such particles are shown below. The PMT measurements (range vs. time) are compared to the range vs. time the particle would have if it maintained its entry velocity (the blue line) and if it followed a simple ablation model (the black line) [6].



The measurements appear to indicate some slowdown, in line with the drag model. For a particle slower than 20 km/s, we might see slowdowns of about 1-3 km/s before the particle fully ablates or reaches the end of the chamber.

Future Work: A new pickup-tube detector will be added to the entrance of the ablation chamber to determine the time when particles enter the chamber. Combined with a timing measurement form the impact detector, the new detector will observe slowdown. Future modeling efforts will also to compare Al ablation and charge production models to the observed charge profiles.

Conclusions: Using the data, we calculated the values of β for simulated aluminum meteors and found the Jones parameter for aluminum. However, Jones is a poor fit to the observed data. We also observed slowdown of the aluminum particles using a PMT array. Slowdown biases our measurements to be lower limits on the true β values, setting a lower limit on meteoroid detectability using HPLA radars.

References: [1] Jones, W., Theoretical and Observational Determinations of the Ionization Coefficient of Meteors. Mon. Not. R. Astron. Soc. 288, 995-1003 (1997). [2] http://solarsystem.nasa.gov/galleries/perseid-meteor-over-west-virginia [3] Plane, J.M.C., Cosmic Dust in the Earth's Atmosphere. Chem. Soc. Rev. 41, 6507-6518 (2012). [4] https://apod.nasa.gov/apod/ap970416.html [5] Simolka, J., Design, Manufacture, and Testing of an Experimental Set-Up Simulating Meteoric Ablation in Laboratory Conditions. Diploma Thesis (2013). [6] Vondrak, T., et al, A Chemical Model of Meteoric Ablation. Atmos. Chem. Phys. 8, 7015-7031 (2008).