Measurements of the Drag Coefficient of Simulated Micrometeoroids

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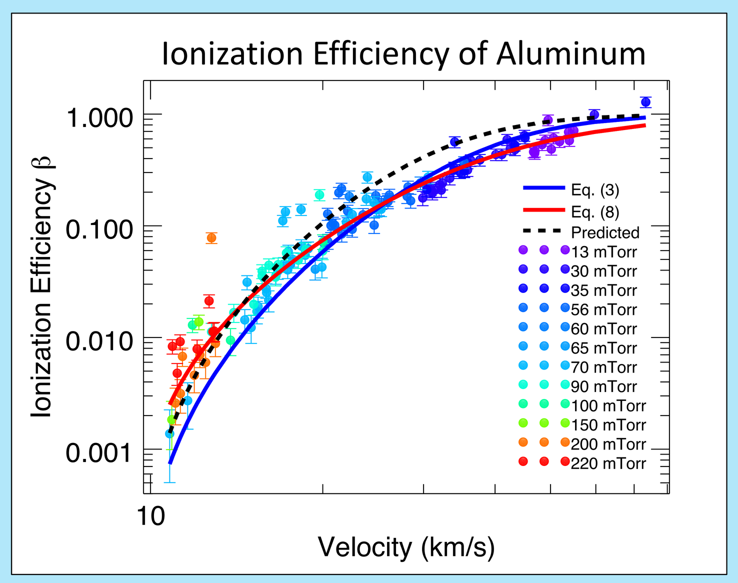
Introduction

When meteoroids enter Earth's atmosphere, most ablate at high altitudes. These meteors deposit metals into the mesosphere and constrain models of interplanetary dust in our Solar System. To study the ablation process, meteors are simulated in the laboratory using the University of Colorado's dust accelerator facility. So far, the ionization and ablation of Fe and Al have been studied in this facility, and future ablation studies will look at more complex compositions. In this study, the slowdown of simulated meteors in an air chamber was measured to calculate the drag coefficient for meteors. The drag coefficient was higher than predicted, which has implications for the entire ablation process since drag is coupled to heating and ionization.

Image Credit: Jimmy Westlake (jpl.nasa.gov)

Meteor Ablation



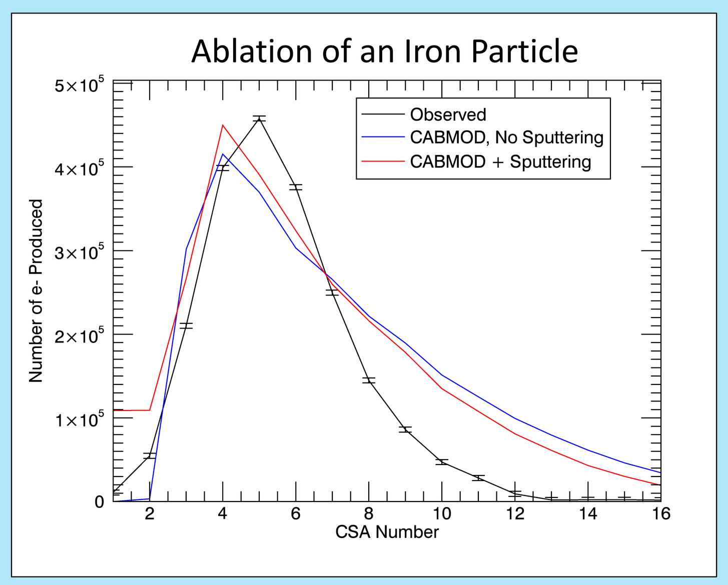


Figure from DeLuca, et al. (2017)

Past studies by Thomas et al. (2016) and DeLuca et al. (2017) have focused on the ionization produced by meteors. Total ionization is measured to study the ionization efficiency, and the spatial charge production is measured to study the full ablation process, including heating, drag, and ionization. Ablation can be modeled with equations by Vondrak et al. (2008) for the drag, heating, and mass loss given below.

The plot on the left above provides the ionization efficiency β of Al, which is the ratio of charges produced to atoms ablated, as measured by DeLuca, et al. (2017). Meteor slowdown will reduce β, making the meteors less detectable by radar. The spatial charge production due to the heating of an Fe particle is observed on the right, which is coupled to the slowdown as seen in the model equations.

$$\frac{\pi}{2}R^2 v^3 \rho_a \Lambda = 4\pi R^2 \epsilon\sigma(T^4 - T_{env}^4) + \frac{4\pi}{3}R^3\rho_m C\frac{dT}{dt} + L\frac{dm}{dt}$$

$$\frac{dm}{dt} = 4\pi R^2 \gamma p\sqrt{\frac{\mu}{2\pi k_B T}} \qquad \frac{dv}{dt} = -\frac{3\Gamma v^2 \rho_{air}}{4R\rho_{meteor}}$$

We measured the **drag coefficient** given in the drag equation. It is typically **assumed between 0.5 and 1** for spherical particles.

Experimental Setup

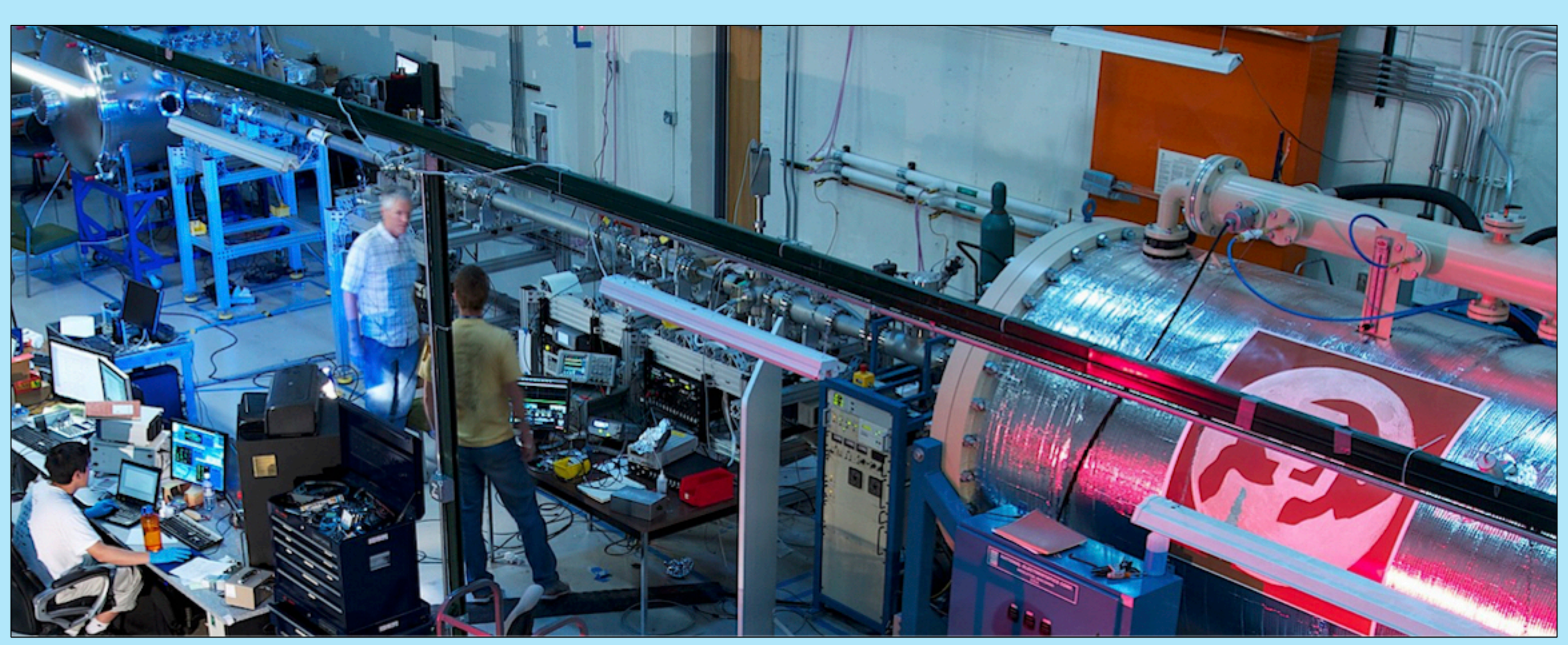
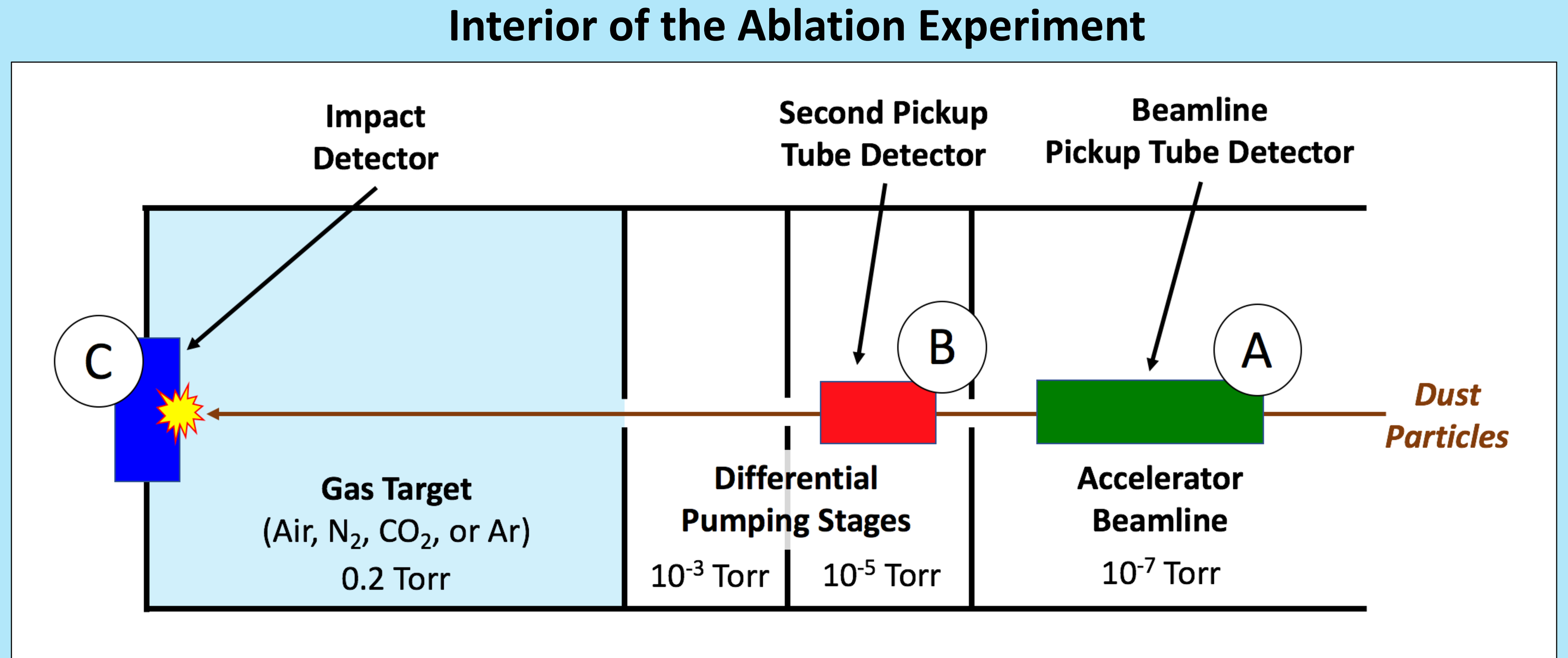


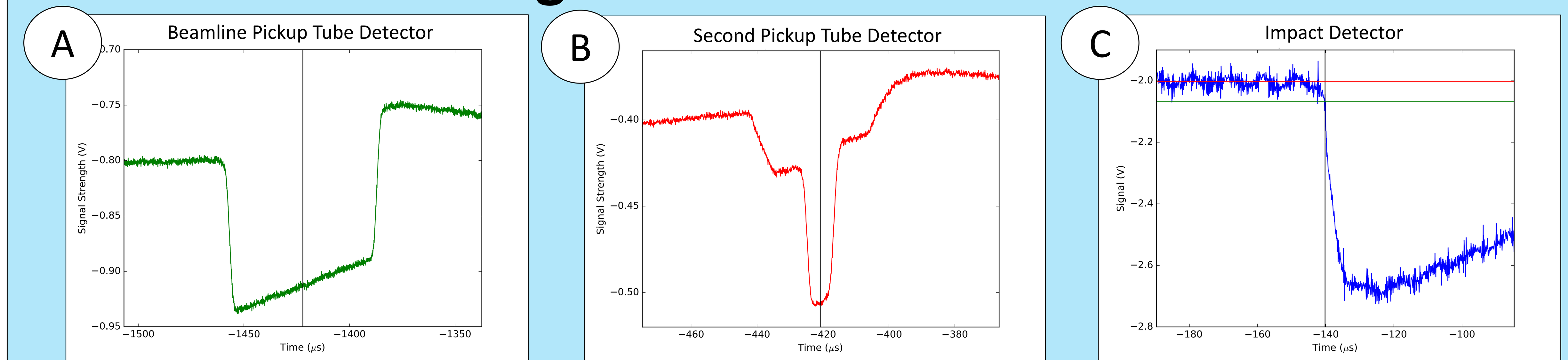
Image Credit: impact.colorado.edu

The dust accelerator at the University of Colorado was used to shoot submicron Al particles into a gas target. The target held gas at a constant pressure of 200 mTorr, and DSMC simulations were used to confirm that the density variation inside the chamber is negligible. To measure slowdown, two pickup tube detectors were used to track the particles before they entered the air chamber. An impact detector timed when the particles reached the end of the chamber. The pickup tubes and the impact detector were equipped with high-speed A250 charge sensitive preamplifiers to provide sub-microsecond timing resolution. The distance between the detectors was carefully calibrated by shooting particles of known velocity into the chamber while at vacuum. The precise timing and distance measurements allowed the slowdown of the particles due to air drag to be measured.

Interior of the Ablation Experiment



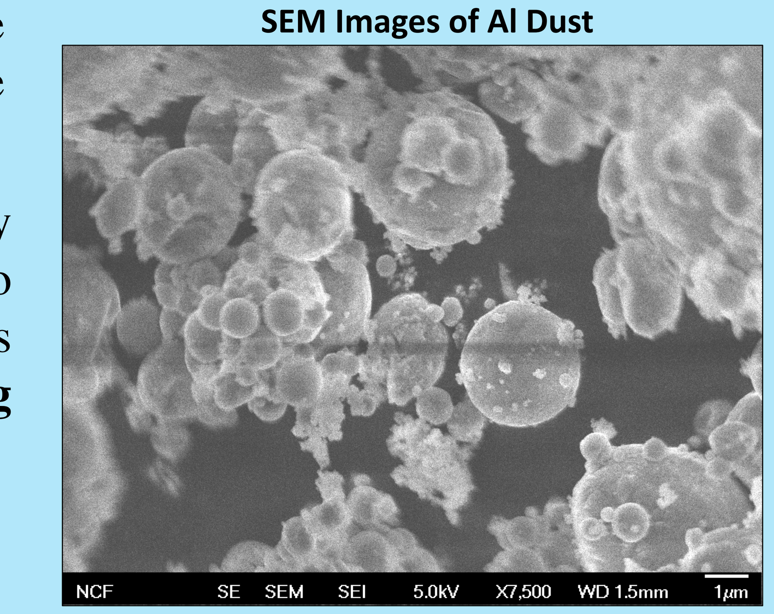
Drag Coefficient Calculations

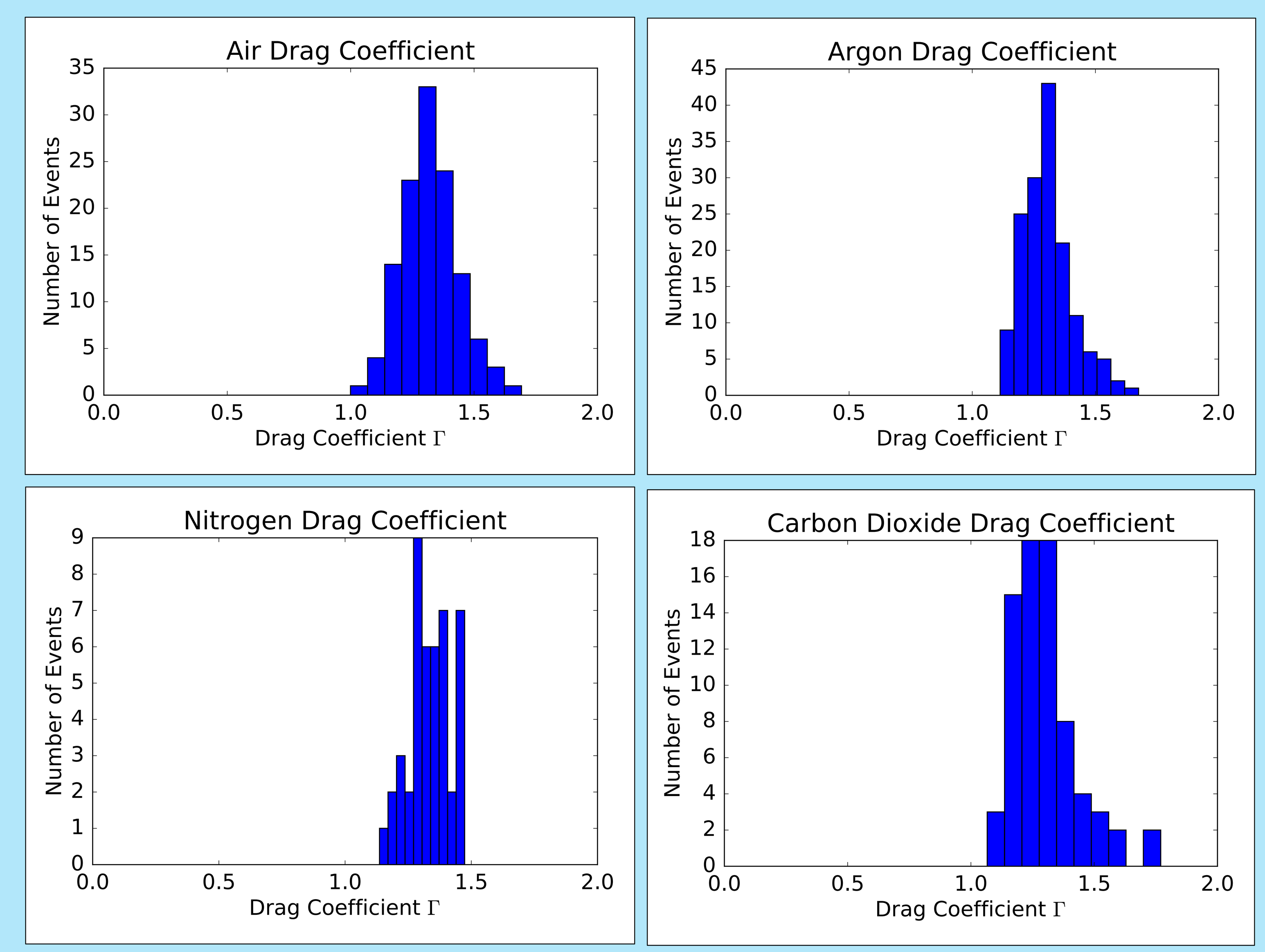


Using the precise timing measurements from the two pickup tube detectors and the impact detector, the slowdown of each particle from its initial velocity could be measured. Typical detector signals are shown above.

The Al particles used in the experiment were assumed to be spherical, as verified by SEM images. Particles between 1-10 km/s and about 1 micron diameter were used to limit heating and subsequent mass loss by the particles, so that the radii of the particles would remain constant. **Under the assumption of constant radius, the drag coefficient can be calculated directly from the drag equation.**

SEM Images of Al Dust





Results

Meteor impacts with air, pure nitrogen, argon, and carbon dioxide were studied. The drag coefficients for individual dust particles striking the 4 gases are shown in the histograms. The calculated coefficients are:

Air: $\Gamma = 1.32 \pm 0.12$

N_2: $\Gamma = 1.34 \pm 0.08$

Ar: $\Gamma = 1.29 \pm 0.10$

CO_2: $\Gamma = 1.28 \pm 0.13$

The drag coefficient is similar for different gases, indicating that the impact physics is species independent at these velocities.

Conclusions and Future Work

The drag coefficients are significantly larger than 1, allowing us to **reject the hypothesis that the drag coefficient should be 1 or less for air** ($p < 0.005$). It is usually assumed that the drag coefficient is between 0.5 and 1, so these results indicate that **meteors may experience more drag than usually assumed**. A higher drag coefficient would reduce heating and ionization, thus reducing meteor detectability by radars. Further work is needed to understand why the drag coefficient is higher than expected. This work will be done by modeling the drag process in order to match the current results to a comprehensive theory which accounts for specular versus diffuse reflection and accommodation of the gas molecules to the particle surface.

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References:

- DeLuca, M., et al. Planet. Space Sci., In Press (2017).
- Thomas, et al. Geophys. Res. Lett. 43, 3645-3652 (2016).
- Vondrak, T., et al. Atmos. Chem. Phys. 8, 7015–7031 (2008).