ESTIMATING THE DRAG COEFFICIENTS OF METEORITES FOR ALL MACH NUMBER REGIMES.
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Accurate values for the drag coefficient are essential to determine the trajectories that meteoroids follow during atmospheric entry. Most models that describe the descent of meteors or witnessed falls find that a constant drag coefficient, Γ, of 0.7 reproduces the observations rather well (e.g. [1], [2]).

However, experimental data obtained from studies of regular solids indicate that the drag coefficient is a strong function of Mach number, especially in the low supersonic and subsonic Mach regimes (see Figure 1). For instance, Γ for a sphere ranges from less than 0.5 at subsonic speeds, rapidly increases to ~1 in the transonic regime, and levels off to about 0.9 in the hypersonic limit.

When estimating the aerodynamic properties of meteorites, it is helpful to assume that they are aerodynamically similar to a simple shape. Although meteorites are not perfect spheres, it is likely that their drag coefficients follow a similar trend, such that Γ drops by a factor of ~2 as the bolide slows from supersonic to subsonic speeds. These generalizations provide a framework for a meteorite's drag coefficient function to be dependent on Mach number, such that Γ decreases as the meteorite's speed decreases.

If the Γ of 0.7 represents every portion of the bolide's flight, current models may be significantly overestimating the drag in the subsonic regime, and underestimating the drag in the supersonic and hypersonic regimes.

To address this issue, we present a numerical method to calculate Γ as a function of Mach number. This method can be used to more accurately model the trajectories of meteors, particularly the dark-flight portion. First we gather drag coefficient data for spheres in every Mach number regime [3], [4]. It is especially important to have experimental data during Mach number regime changes. Spheres are aerodynamically simple objects, and drag coefficient data from past experiments is plentiful. We can derive a best fit function over the data points to estimate drag values in between measurements. This best fit function is composed of two base functions that connect in the subsonic regime. During the majority of the subsonic regime, Γ is represented by a quadratic function. At speeds slightly less than Mach one, the best fit function switches to the second base function, which is a sum of two exponentials:

$$\Gamma_{bf}(M_\infty) = 2.1e^{(-1.2(M_\infty+0.35))} - 8.9e^{(-2.2(M_\infty+0.35))} + 0.92$$

The hypersonic limit of this function matches closely with that of the Modified Newtonian Theory for blunt bodies. Newtonian theory has its origins in Newton's *Principia.* It was originally presented as a method for describing low-speed flows, but proved to be inaccurate in the subsonic regime. However for hypersonic speeds it is very accurate because shock waves at these speeds are extremely close to the surface of the objects generating them. Modified Newtonian theory was introduced in 1955, and changes the pressure coefficient used in the original theory to a maximum pressure coefficient [5]. Using MNT, the drag coefficient for spheres, $\Gamma(M_\infty)$, is written as a function of Mach number by letting the drag equal one half of the maximum pressure coefficient. The symmetry of a sphere allows its drag to be expressed as a function of Mach number only .With this change, the equation for the drag coefficient of a sphere is

$$\Gamma(M_\infty) = \frac{1}{2}\left\{\frac{2}{\gamma M_\infty^2}\left\{\left[\frac{(\gamma+1)^2 M_\infty^2}{4\gamma M_\infty^2 - 2(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{1-\gamma+2\gamma M_\infty^2}{\gamma+1}\right]-1\right\}\right\}$$

Assuming a constant ratio of specific heats (γ) of 1.4, the limit as M∞ approaches infinity is 0.92. The limit of the best fit function is also 0.92. This shows that the best fit model agrees with mathematical methods for finding Γ in the hypersonic regime.

This best fit drag profile was used in a program created to model the descent of meteoritic fragments through the atmosphere. During these tests the fragments were assumed to be spherical meteoroids. We will present results comparing the trajectories of bolides using a drag coefficient of a constant value of 0.7, and also as drag as a function of Mach number. The difference between these two drag profiles will affect the range of the bolides and the shape of their trajectories.

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Figure 1. Drag coefficient as a function of Mach number for a sphere. Here we can see that the drag coefficient changes by a factor of ~2 as the Mach number increases. The solid lines are data from two experiments designed to find the drag coefficient of spheres at different Mach numbers. The solid red line is data from A. C. Charters and R. N. Thomas [1]. The solid magenta line is from A. J. Hodges [2]. The dotted blue line is the best fit function. The line of circles is Modified Newtonian Theory. Note that MNT only begins to become accurate above Mach 5.