Experimentally determined luminous efficiency measurements applied to photometric meteor masses

Liane K. Tarnecki[1], Robert A. Marshall[1], Zoltan Sternovsky[1,2], Peter Brown[3], and Tobin Munsat[1]

1. University of Colorado Boulder
2. Laboratory for Atmospheric and Space Physics
3. Western University

Introduction

Material deposited by meteors ablating in the upper atmosphere can have significant effects on atmospheric dynamics, via changed densities, conductivities, and compositions. Characterizing and constraining this input is important for understanding the mesosphere/lower thermosphere (MLT) and the E region ionosphere and correctly modeling large scale dynamics. However, mass flux estimates calculated using different techniques vary widely. Many methods of measuring this parameter exist, each with associated biases and errors. The result is a discrepancy of several orders of magnitude in determinations of the total meteor mass flux. This work focuses on an effort to make improved measurements of one physical property, the luminous efficiency, using laboratory experiments, and to apply the results to observed optical meteors in order to calculate photometric masses.

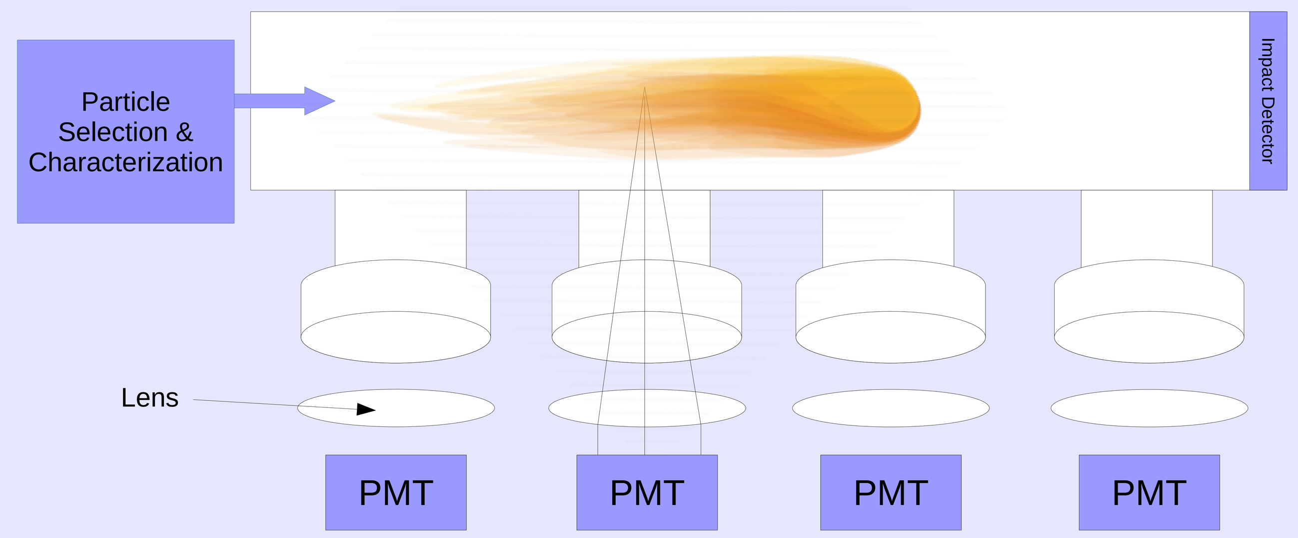
Luminous Efficiency

The luminous efficiency (τ) characterizes the fraction of a meteor's kinetic energy (E_k) that is converted into light output during ablation. This property has been measured in the lab and determined from observations, with large variation in the results.

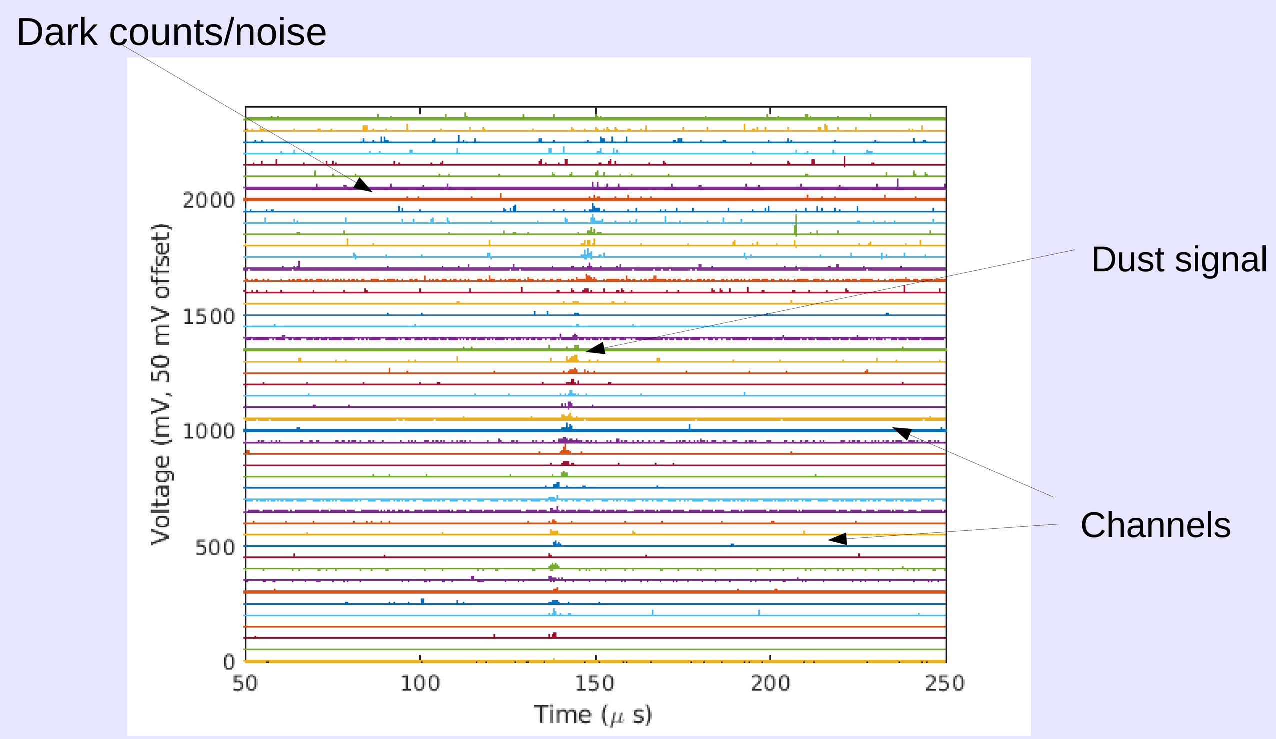
$$L = -\tau \frac{dE_k}{dt} = -\tau \frac{d}{dt}\left(\frac{1}{2}mv^2\right) = -\tau\left(\frac{1}{2}\frac{dm}{dt}v^2 + mv\frac{dv}{dt}\right)$$

The second term characterizes the deceleration of the meteoroid as it ablates. Since deceleration is usually minimal, this term is often neglected. The remaining terms are the luminosity (L), mass (m), and velocity (v). Therefore, in order to calculate the mass one generally must know the luminous efficiency ahead of time, and vice versa.

Luminous Efficiency Experiment



1. 3 MV electrostatic generator accelerates dust particles along a vacuum tube at 10+ km/s, recording their mass and velocity
2. A particle enters a pressurized ablation chamber, fitted with four viewing windows
3. The particle begins to ablate; light is emitted from the 'meteor'
4. Lenses collect and focus the light
5. Photomultiplier tubes (PMTs) amplify the signal
6. PMT outputs are collected and digitized by a data acquisition system



Example Data

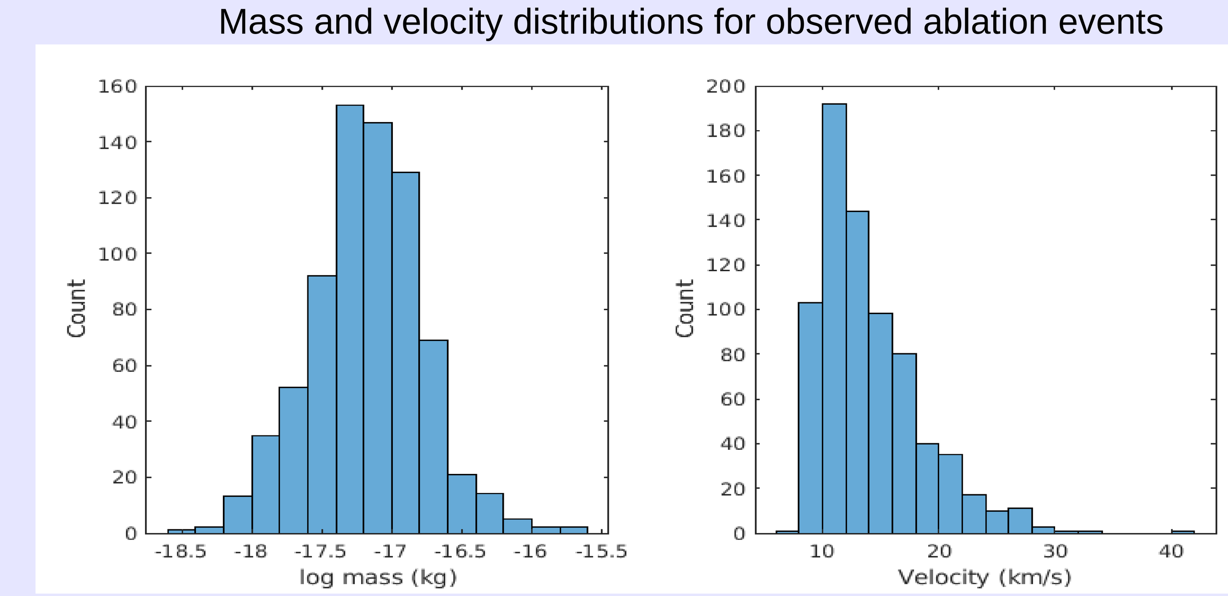
Count Incident Photons (per channel)
Convert raw voltages to photon counts using calibration relationship

Calculate Photon Production
Assume isotropic emission and account for transmission rates for lenses and windows, then integrate over time for each channel and sum channel totals

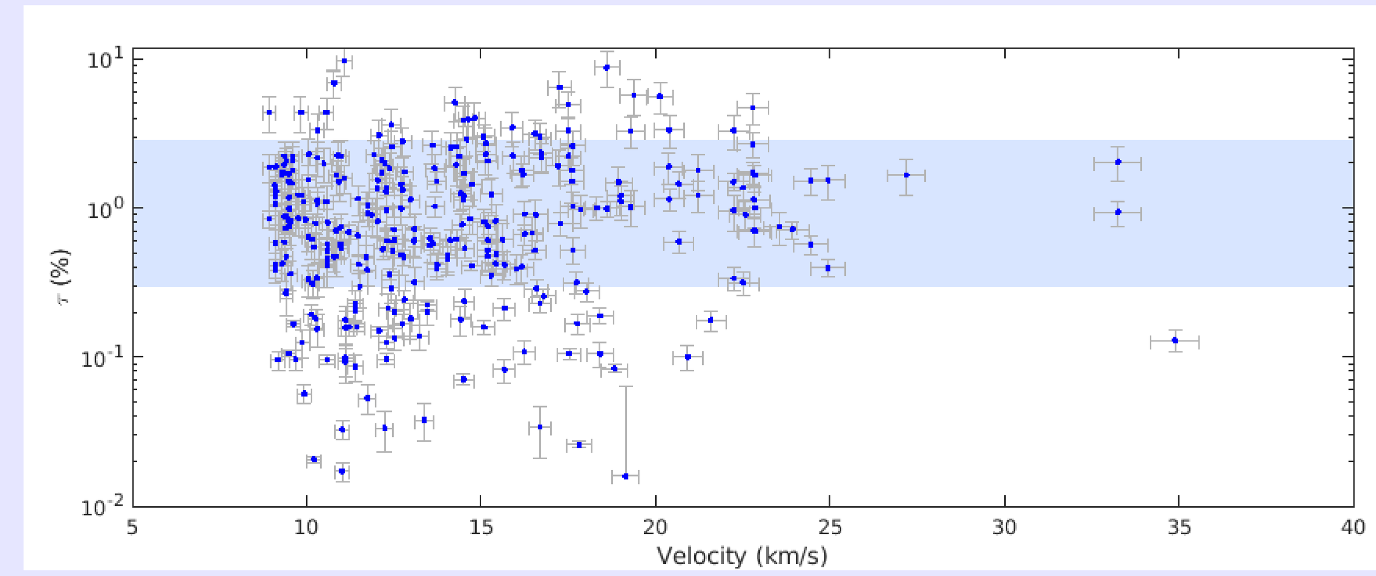
Calculate Luminosity
$L = E_{photon} n_{photons}$
Assume photon wavelength of 374 nm

Calculate Luminous Efficiency
$\int L = -\tau \int dE_k/dt = -\tau(\frac{1}{2} mv^2)$
Assume τ is constant with time

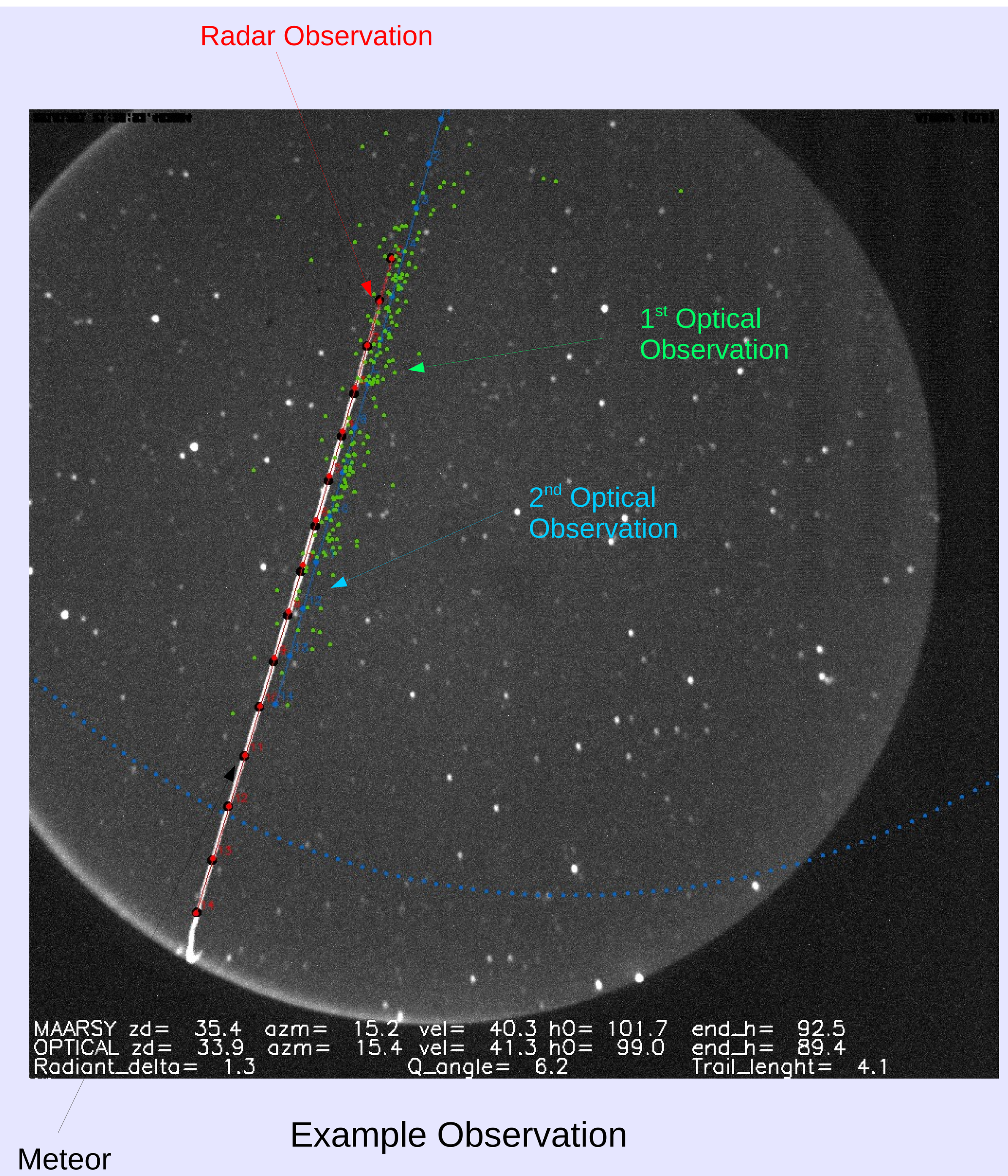
Mass and velocity distributions for observed ablation events



- τ was calculated for 804 observed optical signals
- There is a slight trend with velocity, where slower particles are more likely to have small luminous efficiencies
- The median value is 1%; the 1-sigma range is 0.3-3%
- The data show large spread, which is as yet unexplained



Photometric Mass Determination



Example Observation

Dataset

165 simultaneous meteor observations

- Radar
  - MAARSY (53.5 MHz)
  - Altitude, velocity, RCS
- Optical
  - 2 wide-field cameras
  - Altitude, position, magnitude

Calculate Luminosity and Velocity
Use magnitude-luminosity relationship and position/timing information to calculate luminosity and velocity at each point.

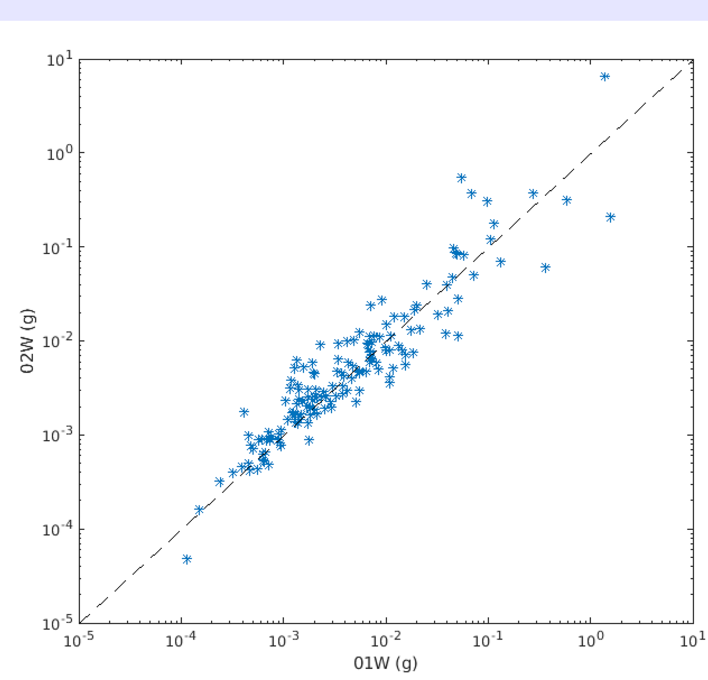
Calculate Change in Mass

$$L = -\tau\frac{dE_k}{dt} = -\tau\left(\frac{1}{2}\frac{dm}{dt}v^2\right) \Rightarrow \frac{dm}{dt} = -\frac{2L}{v^2\tau}$$

Estimate Mass
Integrate mass lost at each timestep over the observation to estimate the total mass.

Results

- Using the 1% luminous efficiency determined in the experiment, the photometric mass is calculated for each observation
- Masses are typically mg-g
- Events observed by both cameras show good agreement between the independently-calculated masses (right)
- There is more spread between the two masses for larger events, implying that these events might undergo some process by which the observed light depends on the position and angle of the observation (e.g. fragmentation)



Compare to Radar Masses

- Radar masses are calculated using the FDTD model based method in Tarnecki and Marshall (2021)
- Some events show good agreement, but on average the photometric masses are an order of magnitude larger than the radar masses (right)
- This discrepancy could be explained by a failure of the radar mass method for large meteors at MAARSY's frequency
- This possibility will be addressed in future work by repeating this analysis on a set of data that includes measurements by the EISCAT radar, as well as optical and MAARSY measurements