CONSTRAINING PHYSICAL PROPERTIES USING METEOR OBSERVATIONS

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Introduction:

Meteors are produced from meteoroids that are Near Earth Objects (NEOs). Some of these meteoroids represent the most primitive material in the solar system, and while most may pose no direct impact threat to the Earth, they provide a means to better understand those objects which do. Produced through the disruption of a much larger comet or asteroid, their study can help infer the chemical and physical properties (composition, structure, mass, porosity, density, thermal, etc.) of these parent bodies. Unfortunately, their non-destructive collection is a complicated and expensive task, meaning they cannot easily be directly studied in a laboratory. However, they can interact with the atmosphere to create ionised trails of electrons and photons: meteors. These can be detected by ground-based instruments, allowing for the study of meteoroids that are much smaller (mm to cm sized) than those directly visible in space, without the expense of a sample return mission. Here we give a quick overview of meteoroid ablation, methods to observe them, and highlight improvements (such as Weryk and Brown, 2013; Campbell-Brown et al., 2013; Stokan and Campbell-Brown 2015) that can be applied to ablation models that currently do not reproduce the micro-physical details resolvable by modern instruments.

Meteoroid Ablation:

Many specific implementations of a meteoroid ablation model can be found in the literature (see for example, Campbell-Brown and Koschny, 2004; Borovička et al., 2007), but most are based on similar physics where momentum and energy are transfered due to collisions with air molecules (but see Boyd, 1998). The simplest picture of a meteoroid is a spherical object of uniform composition that enters the atmosphere and heats up while colliding with air molecules. As it heats, material ablates off (referred to as thermal ablation) and further collides with other atmospheric molecules to create a trail of electrons and photons. Classical ablation theory (see McKinley, 1961) predicts that light emission occurs only after a meteoroid has reached its boiling temperature, and that before this time, energy gained from collisions with air molecules is used only for heating. More recent ablation models (Adolfsson and Gustafson, 1996; Campbell-Brown and Koschny, 2004; Hill et al. 2004) have improved upon this, and use the Knudsen-Langmuir equation to quantify the mass loss at any point in time, even when the meteoroid temperature is below its boiling point.

A more realistic physical picture of a meteoroid might be best described as a dust-ball (Hawkes and Jones, 1975), which is a collection of solid grains held together by a volatile 'glue' (a necessary model construct, even though its nature is not known). Heating of the glue proceeds until its melting point, when grains are released which independently undergo thermal ablation. The total electron and photon count is a composite of all grains. In addition to thermal ablation, realistic meteoroids may fragment, either into relatively large pieces, or into finer scale meteor wake (see Figure 1). Large scale fragmentation will show a sudden increase in light production, while wake will 'flow' directly behind the meteoroid as it ablates. Fragmentation can occur in a transverse direction to the meteor motion (see Stokan and Campbell-Brown, 2014).

By integrating the standard differential equations that describe the time evolution of mass, speed, and temperature (see McKinley, 1961), a simulated meteor may be generated and compared to real observations. By adjusting the model parameters until the simulated meteor agrees with observation, the physical parameters (density, composition, thermal properties) of the meteoroid can be inferred. The atmospheric mass density is typically taken from an atmospheric model such as MSIS-E90 model (Hedin, 1991).

Observations:

The most common two methods of observing meteors are with radar and video instruments. Specular radar systems, such as the Canadian Meteor Orbit Radar (CMOR) described by Jones et al. (2005), are well suited for studying the faintest meteors. Radio pulses are reflected off the electrons in a meteor's ionised trail, which are then detected by multi-station receivers that can determine the heliocentric orbit for up to 10^4 meteors per day. These systems are ideal for determining the mass influx that arrives at the Earth, including daytime meteors. However, due to observing biases, they are only sensitive to about 5% of meteors, and do not see the entire meteor trail, but rather only where a specular reflecting condition is met. Further discussion about radar observations can be found in Ceplecha et al. (2001) or Weryk and Brown (2013).

Video systems on the other hand, while not as sensitive as radar systems, do not suffer from the same observation biases. Because the meteoroid is directly imaged, a better idea of its morphology is obtained.

At least two video stations are required in order to find heliocentric orbits, which can be combined with the results of ablation modelling to map physical properties as a function of location in the Solar System. An example is given by Kikwaya et al. (2011). The most modern video meteor system is the Canadian Automated Meteor Observatory (CAMO), described by Weryk et al. (2013). This system uses a guided telescopic camera to track meteors in real-time with a small field-of-view. One limitation of video systems, however, is that the conversion efficiency to produce photons is not as well known as the efficiency for producing electrons. Weryk and Brown (2013) made simultaneous radar-video observations of the same meteors to produce an independent estimate of the photon conversion efficiency.

Trail Evolution:

After a meteoroid has ablated, the electrons produced are still present. The trail will expand due to ambipolar diffusion, which decreases the amount of power reflected. Electron attachment and recombination will remove the electrons more quickly than diffusion alone, and this process can be used to model the elemental composition of ions in the trail based on the known chemistry rate coefficients. This procedure is described in detail by Ceplecha et al. (2001).

Sample Observation:

Figure 1 shows successive frames from a meteor recorded by the CAMO system on 20150329. This object which entered the atmosphere with an entry angle of 43° at a speed of $19.4\,\mathrm{km/s}$ took about two seconds to ablate. An ablation model (Weryk, in preparation) was fit to the observation, with the light curve given by Figure 2. The resulting mass of $4{\times}10^{-4}\,kg$ and bulk density $3600\,kg/m^3$ best fit the light curve. While this meteor's parent body is currently unknown, observation of meteor showers (which share the same parent body) will shed light on the properties of a specific NEO.

References:

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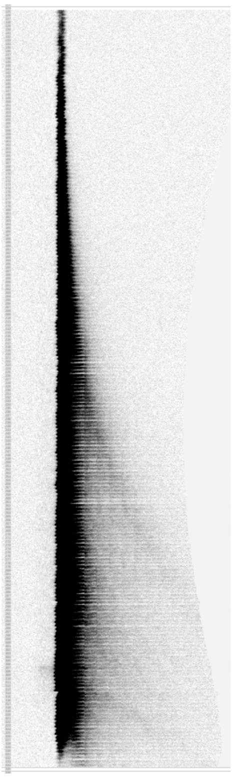

Figure 1: **This meteor was detected by the Canadian Automated Meteor Observatory (CAMO) on 20150329. Successive frames are layered horizontally, which shows the dynamic morphology of meteor wake. Time increases from top to bottom, with this meteor lasting approximately two seconds. It entered the atmosphere with an entry zenith angle of 43° at a speed of $19.4\,\mathrm{km/s}$**

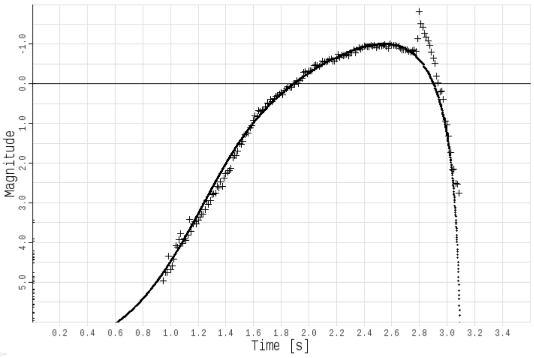

Figure 2: **The light-curve of the sample meteor in Figure 1. An ablation model (Weryk, in preparation) was used, with the model parameters being tweaked until the simulated meteor matched the observation. In this case, the mass is $4{\times}10^{-4}\,kg$, with a bulk density of $3600\,kg/m^3$. The sharp increase towards the end of the light curve is caused by a larger scale fragmentation event, which is not handled by the current model.**