Abstract

Determination of asteroid bulk density is an important aspect of NEO characterization, yet difficult to measure. As a fraction of meteoroids originate from asteroids (including some NEOs), a study of meteoroid bulk densities can potentially provide useful insights into the densities of NEOs and PHOs in lieu of mutual perturbations, satellite, or expensive spacecraft missions.

NASA's Meteoroid Environment Office characterizes the meteoroid environment for the purpose of spacecraft risk and operations. To accurately determine the risk, a distribution of meteoroid bulk densities are needed. This is not trivial to determine. If the particle survives to the ground the bulk density can be directly measured, however only the most dense particles land on the Earth. The next best approach is to model the meteor's ablation, which is not straightforward. Clear determination is necessary to do this and there are discrepancies in results between models.

One approach to a distribution of bulk density is to use a measured proxy for the densities, then calibrate the proxy with known densities from meteorite falls, ablation modelling, and other sources. An obvious proxy choice is the Ceplecha type, $K_B$, thought to indicate the strength of a meteoroid.

$K_B$ is frequently cited as a good proxy for meteoroid densities, but we find it is poorly correlated with density. However, a distinct split by dynamical type was seen in ablation modelling, and other sources. An obvious proxy choice is the Ceplecha type, $K_B$, thought to indicate the strength of a meteoroid.

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Table 1: Distributions of $K_B$ in NASA Wide-field meteor camera.

<table>
<thead>
<tr>
<th>Group</th>
<th>$K_B$ Range</th>
<th>Distributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$10^{-5}$ - 1</td>
<td>Wide</td>
</tr>
<tr>
<td>B</td>
<td>$10^{-5}$ - 1</td>
<td>Medium</td>
</tr>
<tr>
<td>C</td>
<td>$10^{-5}$ - 1</td>
<td>Narrow</td>
</tr>
<tr>
<td>D</td>
<td>$10^{-5}$ - 1</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

Meteoroid densities associated with Ceplecha types

In order to use $K_B$ as a proxy for density distribution, the link between $K_B$ and density must be established. The earliest studies on meteoroid bulk density were from the 1950's. Since then, many studies have been performed.

In examining the various sources that have linked density to $K_B$, the relationship was not as clear as one would hope and primarily based on studies that have significant biases or models that have time dependent properties such as single-body ablation. Other discrepancies likely stem from a paucity of data. Several of Ceplecha's papers relied on meteorite density data from two or three meteorite falls, or just one fireball (Ceplecha, 1977, 1988, Ceplecha et al., 1993). Table 2 show seven of the best studies. Even within these studies, much is unclear and unknown. Note the discrepancies, particularly in Groups A through D.

Ceplecha types

In 1958, Ceplecha introduced a parameter, $K_B$, that he saw as a measure of the strength of a meteor and was linked to meteoroid densities (Ceplecha, 1958).

It was noted that the beginnings heights, $H_B$, of meteoroids were correlated to their strength based on measured $H_B$ of more porous meteoroids (Dracooids) or more dense meteoroids (Geminoids). $H_B$ is most affected by velocity, separate bands can clearly be seen when plotting $H_B$ against velocity. Ceplecha thought these bands were correlated with meteoroid strength.

What is $K_B$? Based on a expression from Levin (1956) for surface temperature of a meteoroid per meter:

$$T(h) = \alpha \frac{h}{\sqrt{\pi D_0}} e^{-\frac{h}{\delta}}$$

$T(h)$ is surface temperature at a height $h$ above the earth's surface, $\delta$ is a meteoroid density, $\alpha$ is the accommodation coefficient, $h$ is the specific heat of the meteoroid material, $D_0$ is the density gradient, $\alpha$ is the ambient velocity, $T$ is the earth's surface temperature.

If the surface temperature and air density are set to values at the meteor beginning height, Ceplecha put all the physical constants on one side and observable quantities on the other, and set the physical constants are set to $K_B$:

$$K_B = \log(\rho_e) + 2.5 \log(\omega) - 0.5 \log(\cos(\theta))$$

Where $K_B$ is a function of material constants and surface temperature, and changes in $K_B$ are strongly tied into the composition of the meteor.

Ceplecha (1958) found several $K_B$ groups that show up when isolating the meteoroids and $K_B$ values by velocity and orbital type, as seen in Table 1 and Figure 3.

The most thorough study of bulk densities through ablation modelling is Kikwaya et al. (2011). They looked at 107 meteors observed by intensified cameras in Ontario, Canada and modelled the deceleration and light curves with an ablation model that includes fragmentation (Campbell-Brown & Rosicky, 2004). They robustly searched the entire parameter space to determine fits to the data. A subset of the 92 events not associated with a shower was used. Campbell-Brown et al. (2013) inspected 10 meteors using the same model. Orbits and trajectories were given for the meteors. With this study, we look at trends in $K_B$.

The correlation between $K_B$ and bulk density was not as strong as hoped. However, a clear relationship between $T_B$ and density was seen. A Spearman rank coefficient of 0.7-0.8 was found between density and $T_B$, and 0.41 between $K_B$ and density, indicating a tighter correlation between $T_B$ and density.

Conclusions

The task of determining meteoroid density distributions is complex and led to the investigation described in this paper. In reproducing work done by Ceplecha (1977, 1988) to correlate $K_B$ with bulk density, we examined the modeling of high-resolution meteor data from Campbell-Brown et al. (2013) and Kikwaya et al. (2011). The correlation between $K_B$ and density was not as strong as hoped.

The Tisserand parameter of a meteoroid is a better indicator of the density than the strength proxy, a somewhat surprising result.