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 could 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 deceleration 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. As obvious proxy choice is the Ceplecha type, Ke, thought to indicate the strength of a meteoroid.

Ke 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 with Johann Tisserand parameter, TP, with meteoroids from Halley Type comets (TP < 2) exhibiting much lower densities than those originating from Jupiter Family comets and asteroids (TP > 2).

Ceplecha types
In 1958, Ceplecha introduced a parameter, Ke, 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 beginning heights, H0, of meteoroids were correlated to their strength based on measured H0 of more pores meteoroids (Dracoids) or more dense meteoroids (Geminids). H0 is most affected by velocity, but separate bands can clearly be seen when plotting H0 against velocity. Ceplecha thought these bands were correlated with meteoroid type.

What is Ke? Based on a expression from Levin (1956) for surface temperature of a meteoroid per height:

\[
\tau(0,h) = \frac{\alpha}{2 \sqrt{2 \pi CD}} \rho a^2 \cos^{-1} \left( \frac{1}{a} \right) \]

\( \tau(0,h) \) is surface temperature at a height
\( \alpha \) is heat conductivity
\( \rho \) is meteoroid density
\( a \) is the accommodation coefficient
\( s \) is the specific heat of the meteoroid material
\( h \) is the air density gradient
\( v \) is the approach velocity
\( \beta \) is the air density

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:

\[
K_e = \log(\rho_a) + 2.5 \log(v_a) = -0.8 \log(\cos(\theta))
\]

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

Ceplecha (1958) found several Ke groups that show up when isolating the meteor heights and Ke values by velocity and orbital type, as seen in Tables 1 and 3.

<table>
<thead>
<tr>
<th>Ke group</th>
<th>Ke range</th>
<th>orbital category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>7.30 &lt; Ke &lt; 8.00</td>
<td>8.00 &lt; Ke &lt; 9.00</td>
</tr>
<tr>
<td>Group B</td>
<td>5.50 &lt; Ke &lt; 6.30</td>
<td>6.30 &lt; Ke &lt; 7.10</td>
</tr>
<tr>
<td>Group C</td>
<td>4.80 &lt; Ke &lt; 5.60</td>
<td>5.60 &lt; Ke &lt; 6.40</td>
</tr>
<tr>
<td>Group D</td>
<td>4.10 &lt; Ke &lt; 4.90</td>
<td>4.90 &lt; Ke &lt; 5.70</td>
</tr>
</tbody>
</table>

These groups show up clearly on an H0 vs. velocity graph, further confirming Ceplecha’s suspicion they are tied to the meteoroid strength.

Meteoroid bulk density and Ceplecha types

In order to use Ke as a proxy for density distribution, the link between Ke 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 Ke, the relationship was not as clear as one would hope and primarily based on studies that have significant biases or models that have time dependant work done by a 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., 1998). Table 2 shows seven of the best studies. Even within these studies, much is unclear and unknown. Note the discrepancies, particularly in Groups A through D.

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 & Koschny, 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 Ke.

The correlation between Ke and bulk density was not as strong as hoped. However, a clear relationship between Tisserand Parameter and density was seen. A Spearman Rank coefficient of 0.758 was found between density and Tisserand Parameter. The Spearman coefficient of 0.795 was found between density and Tisserand Parameter of a meteoroid material is a better indicator of the density than Ke. However, this is not a hard cut off as some meteors have Tisserand Parameter of 3 and some asteroids have Tisserand Parameter of 2.

When comparing these results to comets and asteroids, one should note that these bulk densities are for small particles, 10−6 to 10−4 kg. The macroporosity of larger objects will change the overall bulk density. Carry (2012) shows reasonable porosities between 0 and 60%.

Conclusions
The task of determining meteoroid density distributions is complex and led to the investigation described in this report. In reproducing work done by Ceplecha (1977, 1988) to correlate Ke 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 Ke 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.