Meteoroid bulk density and Ceplecha types

R.C. Blaauw1, D.E. Moser2, A.V. Moorhead3

1All Points Logistics/Jacobs ESSSA Group/NASA Meteoroid Environment Office (MEO), Huntsville, AL, 35812, USA, blaaauw.r@Jacobs.com
2Jacobs/ESSSA Group/NASA MEO, Huntsville, AL 35812, USA
3NASA Marshall Space Flight Center/SSA Meteoroid Environment Office, Huntsville, AL 35812, USA

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 is 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 decretion 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 fall, ablation modelling, and other sources. As obvious proxy choice is the Ceplecha type, Kc, thought to indicate the strength of a meteoroid.

Kc is frequently cited as a good proxy for meteoroid densities, but we find it poorly correlated with density. However, a distinct split by dynamical type was seen with Joevian Tisserand parameter, Tj, with meteorites from Halley Type comets (Tj < 2) exhibiting much lower densities than those originating from Jupiter family comets and asteroids (Tj > 2).

Cepela types

In 1958, Ceplecha introduced a parameter, Kc, 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 pure meteoroids (Dracooids) or more dense meteoroids (Gemindoids). H0 is most affected by velocity, but separate bands can clearly be seen when plotting H0 against velocity. Ceplecha thought these bands were Ceplecha groups that show up when isolating the meteors, yet difficult to measure.

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

\[ r(0, h) = \frac{\alpha}{2 \sqrt{\lambda \rho \cos \frac{1}{2} \pi (a_0)} \]  

where \( r(0, h) \) is surface temperature at a height \( h \), \( \lambda \) is heat conductivity, \( \rho \) is meteoroid density, \( a_0 \) is the accommodation coefficient, \( \alpha \) the specific heat of the meteoroild material, \( \beta \) the air density gradient, \( \gamma \) is the specific mass of the radiant, \( v \) the wind velocity, \( \pi \) 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 Kc:

\[ K_c = \log(\rho_0) = 4.6 \text{log}(\rho_0) - 2.5 \text{log}(\rho_0) - 0.5 \text{log}(\rho_0) \]

where \( K_c \) is a function of material constant and surface temperature, and changes in \( K_c \) are strongly tied into the composition of the meteoroid.

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

<table>
<thead>
<tr>
<th>Group</th>
<th>( K_c ) Range</th>
<th>Observational Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>7.89 to 8.00</td>
<td>90% +, ( e_i &lt; 0.05 )</td>
</tr>
<tr>
<td>Group B</td>
<td>5.00 to 7.20</td>
<td>( 0 &lt; e_i &lt; 0.25 )</td>
</tr>
<tr>
<td>Group C1</td>
<td>5.25 to 7.40</td>
<td>( 0 &lt; e_i &lt; 0.45 )</td>
</tr>
<tr>
<td>Group C2</td>
<td>5.00 to 7.10</td>
<td>( 0 &lt; e_i &lt; 0.45 )</td>
</tr>
<tr>
<td>Group D</td>
<td>5.00 to 7.90</td>
<td>( 0 &lt; e_i &lt; 0.45 )</td>
</tr>
</tbody>
</table>

These groups show up clearly on a \( H_0 \) vs. velocity graph, further confirming Ceplecha’s suspicion they are tied to the meteoroid strength.

Table 1: Groups of meteors according to Ceplecha (1958).

Figure 5: \( K_c \) against bulk density on linear barred-of-log plot for 92 meteors. (Kikwaya et al. 2011)

Figure 6: \( Kc \) against bulk density on linear plot for 92 meteors. (Kikwaya et al. 2011)

Figure 7: \( T_j \) against bulk density on linear plot for 92 meteors. (Kikwaya et al. 2011)

Meteoroid densities associated with Ceplecha types

In order to use \( K_c \) as a proxy for density distribution, the link between \( K_c \) 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 \( K_c \), the relationship was not as clear as one would hope and primarily based on studies that have significant biases or models that have inconsistencies or were done by single-body ablation. Other discrepancies likely stem from a paucity of data. Several of Ceplecha’s papers relied on meteoroid 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.

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 \( K_c \) 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 \( K_c \) 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.

Table 2: Average meteoroid density corresponding to different \( K_c \) groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>Density Method</th>
<th>Density of Ceplecha Group (( K_c ) range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>2.0 ( \pm 1.0 )</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>2.5 ( \pm 1.0 )</td>
</tr>
<tr>
<td>C1</td>
<td>3</td>
<td>3.0 ( \pm 1.0 )</td>
</tr>
<tr>
<td>C2</td>
<td>4</td>
<td>4.0 ( \pm 1.0 )</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>5.0 ( \pm 1.0 )</td>
</tr>
</tbody>
</table>

References


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 & Rosceny, 2004). They robustly searched the entire parameter space to determine fits to the data. The 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 \( K_c \).

The correlation between \( K_c \) 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 0.705 was found between density and \( T_j \), and 0.441 between \( K_c \) and density, indicating a tighter correlation between \( T_j \) and density.